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Expert Assessment of Advanced Power Sources

Christopher L. Gardner
March Scientific Ltd.

Defence R&D Canada
CONTRACT REPORT
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July 2007

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1. EXECUTIVE SUMMARY:

In August 2001, DRDC published an exhaustive technical report on technology trends in advanced power sources out to the year 2020. In this report, the authors developed a prioritization of R&D opportunities to help guide the DRDC Advanced Power Source R&D program. Ironically, the above report was published just before the terrorist attacks on the US on 11 September 2001 which resulted in DND adopting a more broadly based defence and national security (counter-terrorism) posture. Moreover, since 9/11, developments in power source technology have advanced at an accelerated pace, internationally, and especially within the US, through programs developed by departments and agencies, such as DARPA.

In light of the rapid development in the field of advanced power sources, and in view of the expanded role of the CF/DND in the defence and security arena, DRDC requested an update of this earlier report to assess current CF/DND needs in advanced power sources to help guide R&D activity in this area. The purpose of the update was to reexamine the advanced power source area in light of the augmented roles of the CF/DND and the advancements in the power source field. This report details the results of this update.

In an initial review, the following eight power source technologies were selected for study.

1. Batteries
2. Fuel Cells
3. Microengines
4. Pulse Power
5. Energy Harvesting
6. Small Nuclear Reactors
7. Radioisotopic Power Sources
8. Hybrid Systems and Power Management

Because of the very wide range of technologies that needed to be examined, the input of a relatively large number of "Technical Experts" was sought. To collect this information, a questionnaire was prepared and distributed to these experts. As part of this questionnaire, the Experts were asked specifically what role nanotechnology is expected to play in the development of advanced power sources. To supplement the information collected from the Technical Experts, the contractor, March Scientific Ltd., also surveyed the various power source areas independently. Following collection of this basic information, an analysis of the ability of the various power sources to meet the requirements of the following important military applications was carried out. Factors identified included total system weight, state-of-development and supply logistics. One of the main outputs of the study has been the preparation of a Technology Readiness Level document for each of the power source technology areas.

1. Power for the Soldier System
2. Tactical Field Power
3. Wireless Sensor Networks
4. Battery Recharge Using Solar Energy Harvesting
5. Central Power for a Remote Base

Based on the information collected during the study, the following are some of the specific recommendations that have been made:

Batteries: Military requirements for advanced batteries (e.g., lithium-ion) will be met, in most cases, through commercial development. Specific areas, such as improvement of low temperature performance and/or power density, may require attention. The use of nanomaterials as the active electrode materials appears to be a promising route for improving the rate capability and low temperature performance of rechargeable lithium batteries.

Small Fuel Cells: Direct methanol and/or chemical hydride polymer electrolyte membrane (PEM) fuel cells appear to have the best chance of meeting the high energy density requirement of the Soldier System as well as other applications including robotic systems and some unmanned air vehicles. There are limitations with both technologies that need to be addressed.

Large Fuel Cells: The need for "silent field power" has long been recognized. Both PEM fuel cells and solid oxide fuel cells (SOFCs) have the potential to meet this requirement. To meet military requirements, ruggedization of SOFCs will be required as well as development of the ability for rapid start-up and shutdown and frequent thermal cycling.

Microengines: Microengines are attractive for demanding applications such as the Soldier System because they offer the possibility of being able to use military fuels. This technology is, however, at an early state of development.

Pulse Power: A wide range of emerging military applications requires very high pulses of power for short duration. This military technology is, in general, highly classified. In order to properly assess the threat and opportunities that these technologies present to the CF, conduct of research in this area will be important.

Energy Harvesting: The development of low cost, flexible photovoltaic materials will open up the possibility of harvesting solar energy for a wide range of military applications. The development of high efficiency thermoelectric materials will offer the possibility for harvesting thermal energy in a variety of military applications. Nanotechnology is expected to play an important role in these developments.

Small Nuclear Power: In the long term, small nuclear systems may be developed to reduce the military's dependence on fossil fuels. Extensive development and regulatory approval is needed to field transportable power systems.

Radioisotopic Sources: Although radioisotopic sources have the potential to provide very long-lived and reliable sources of power, high cost and issues related to security and contamination are likely to limit their application to very specific applications such as in space.

Hybrid System and Power Management: In order to meet many of the demanding requirements, such as the Soldier System requirement, hybridization is going to be necessary. To optimize this process, the development of modelling tools and electronic components is going to be needed. In addition to the development of high energy density power sources, the development of equipment with reduced power consumption will become increasingly important to the CF. Power awareness and power management are increasingly important areas that need to be addressed. A detailed assessment of these energy-reducing technologies is, however, beyond the scope of this report.

Nanotechnology: The use of nanotechnology is expected to have a major impact on the development of some of the advanced power sources to meet the requirements of future military applications. The importance of this area of technology for future development is emphasized.

2. TECHNOLOGY BACKGROUND:

Rapid developments in military and civilian technology are revolutionizing the battlefield and security environments that CF forces will be operating in the future. In many cases, provision of power is limiting size and weight reduction as the size of modern electronics continues to decrease and dependence on portable power is increased. Some examples of such developments are described below:

Soldier System:

It is envisaged that future Soldier Systems (Figure 1) will contain a wide variety of advanced technologies including digital communications, GPS navigation, integrated helmet display, protective clothing, suit cooling and improved weapons. With this system, battery power is becoming a limiting factor as more and more power is going to be needed to meet the requirements of sophisticated electronic and protective systems. Unless sources of power evolve with the systems that use them, they will create a logistics and tactical burden for the soldier.

Figure 1 - Future Soldier System (from [1])

To meet the requirements of future Soldier Systems, DARPA has initiated the "Palm Power Program". This program seeks to develop novel power sources to meet the power needs of future Soldier Systems, small robots, and micro air vehicles. The program is developing compact fuel cell and thermal-to-electric energy conversion technologies. The program has been targeted at the 20 W level, as there are many applications that would benefit, e.g., small robots, future Soldier Systems, and micro air vehicles.

According to DARPA [2] "successful development of a 20 W system will enable scaling to other sizes of interest to DoD. Radically new approaches will be required to meet the specific energy goals of the program, which is on the order of thousands of Whr/kg at the system level. New designs that incorporate novel materials, manufacturing methods, multifunctionality, and thermal management concepts will be essential to the success of this program".

Wireless sensor networks:

Wireless sensor networks (Figure 2) will be used for real time tracking and surveillance, in-situ monitoring of engine and equipment health and environmental monitoring to detect chemical and/or biological hazards. These wireless networks will consist of a large number of tiny nodes each one of which has sensory, communication and computational powers. While the power of any single node is limited, by using mesh-networking protocols, a large mesh of such nodes will be able to transfer information that the sensors have collected by hopping data from node to node until it reaches its destination. The nodes will have the power to reassemble and reconfigure themselves to meet the challenge of a changing environment. The University of California (Berkeley) has developed a minimalist operating system, called TinyOS, for operating such sensor nodes. An indication of worldwide activity is shown by the list [3] of about 70 wireless sensor network projects that are using TinyOS as well as recent DARPA [4] and US Army solicitations [5].

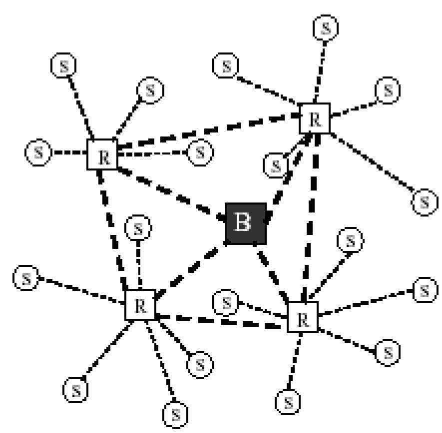

Figure 2 - A Three Level Wireless Network [6]

Pulse Power Systems:

Many emerging military applications will require short, very high power pulses. Such applications include: high power microwave (HPM) and ultra wide band (UWB) weapons, electromagnetic (rail and electrothermal chemical (ETC)) guns, electric armour for military vehicles, non-lethal weapons, burst communications and RF munitions. The characteristics of the pulse power source will depend on the platform that is available to carry the device. With large platforms such as a ship, capacitor based pulsed power systems can be used. Critical research areas that have been identified include: materials development, electromagnetic modelling and thermal management. For gun or missile delivered devices, very compact explosively driven power sources are required [7].

Figure 3 - RPG Protection by Electromagnetic Armour (from [8])

An interesting example (Figure 3) of the use of pulse power is the development [8] by DSTL scientists in the UK of an electric armour system which can resist attack by rocket propelled grenade (RPG) or other shaped charge weapons. DSTL scientists have recently demonstrated an armoured troop carrier protected by electric armour. When hit by a RPG or other shaped charge warhead, the incoming copper jet has to pass through the electrified layers. The high speed copper jet from a shaped charge anti-tank warhead is instantaneously dispersed by the high temperatures and powerful fields generated by the pulsed power system carried by the vehicle. Any residual debris is absorbed by the vehicle's ordinary armoured hull. The system, consisting of bulletproof metal plating, insulation, power distribution lines, and storage capacitors, weighs about two tonnes, but has a protective effect equal to carrying an extra 10-20 tonnes of steel armour.

Robotic Systems:

The development of micro air vehicles and micro robots is expected to give the soldier on-demand information about his surroundings resulting in unprecedented situational awareness. The resulting capability will be especially useful in an urban environment. One of the principal challenges to be overcome is the provision of the necessary power. Small-scale power systems are needed that have very high energy and power densities. Systems with low acoustic and thermal signatures are desirable.

Figure 4 - An Autonomous Battlefield Robot (from [9])

An example of an autonomous battlefield robot designed for the Army is given in Fig. 4. These battlefield robots will have the ability to detect and mark mines, carry weapons, function as tanks, function as "actors" in wireless sensor networks and possibly, in the future, replace soldiers in the battlefield.

Similar problems are also inhibiting developments in civilian technology. Provision of power is limiting developments in cell phone and portable computer technologies. There is considerable civilian interest in developing direct methanol and other fuel cell technologies as a high energy density replacement for lithium ion batteries. It is important to realize, however, that the environmental requirements for a military power source are, in general, much more severe than for civilian technologies. Military system must generally operate over a much wider temperature range, for example, than civilian systems which usually operate near room temperature. Higher power densities and longer operating times are also often needed.

3. OVERVIEW OF FUTURE CF POWER REQUIREMENTS [10]

a) Power for Distributed Sensors and Actuators

In the near future, microelectromechanical (MEMS) sensors and actuators will see widespread use in both commercial and military systems. These new "intelligent microsystems" will interact with their environment by sensing, actuating and communicating without the need for external hardware. Some of the potential military applications for MEMS are listed below.

- Wireless Battlespace Sensors
- Condition-Based Maintenance Sensors
- Structural Health Monitoring Sensors
- Distributed Control of Aerodynamic and Hydrodynamic Systems
- Non-Invasive Biomedical Sensors for the Soldier

To optimize the usefulness of MEMS devices, micro power sources are needed that can be integrated with the other MEMS components. The general requirements for this power source are:

μW - mW power level
Capable of extended duration operation
Energy harvesting from the environment, such as solar, is desirable

b) Integrated Wearable Power Systems

The military personnel can literally wear integrated wearable power systems as part of their suit or equipment. It serves to power all the devices a future soldier would need in the modern battlefield, for example the so-called Soldier System.

The individual soldier will become the mobile platform to execute a combination of combat, surveillance and communication roles in the battlespace. It is envisaged that future Soldier Systems will contain a wide variety of advanced technologies including digital communications, GPS navigation, integrated helmet display, protective clothing, suit cooling and improved weapons. The characteristics of the power source needed to meet these requirements are exceedingly demanding and are going to be very difficult or impossible to meet. At the present time, the best batteries have an energy density of about 350 Wh/kg. Diesel fuel has a theoretical energy density based on the lower heat of combustion of 13,200 Wh/kg. To achieve the target value of 5914 Wh/kg defined by the US Army for their Soldier System, a chemical to electrical energy conversion efficiency of 45% is required. This will be an exceedingly difficult target to meet.

c) Digitized Battlefield

Portable Power Systems serve to power the electronic devices that a soldier needs to carry around. As the volume of equipment increases, also the need for highly sophisticated power sources does in order not to overload the soldier with them and their spares or recharging equipment.

Included in the category of portable electronic equipment are the wide range of portable radios, emergency locator beacons and personal locator beacons used by the CF. Batteries power these devices almost exclusively at the present time. Also night vision goggles, laser range finders and lightweight GPS receivers fall under this category. However, with the demand for increased endurance, range and power output at reduced weight, size and volume, batteries will not be capable of meeting these challenges.

The general requirements for these power sources are:

100 mW - 50 W
Light weight (high energy density)
Low cost
Good low temperature performance (-40 C)
High safety during normal use and abuse
Environmentally acceptable for disposal

d) Miniature Robotic Systems

The development of micro air vehicles and micro robots is expected to give the soldier on-demand information about his surroundings resulting in unprecedented situation awareness. The resulting capability will be especially useful in an urban environment. One of the principal challenges to be overcome is the provision of the necessary power. Small-scale power systems are needed that have very high energy and power densities. Systems with low acoustic and thermal signatures are desirable.

Typical power requirements are:

Power: 10 - 100 W
Silent operation
Liquid fuel operation desirable
Lightweight (> 1000 Wh/kg)
Low thermal signature

e) Tactical Power (Mobile and Stationary)

The Canadian military has a strong requirement for tactical field power. Power is required for command posts, recharging batteries, O&M on equipment, field medicine, messing, water and heat production etc. As the cyberspace becomes an essential tactical and strategic area, advanced power sources will be required to execute various Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR), defensive and offensive functions, including electromagnetic spectrum denial and deception, battlefield networking infrastructure, sensors and Joint Task Force Headquarters, etc. At the present time, diesel engine generators are used for the higher power end (above 100 W), and batteries are used on the low power end. The requirement for tactical power with reduced acoustic, thermal and electromagnetic signature has existed for many years. With the improvement in electro-optic sensors, it will be more difficult to avoid detection. Emissions such as diesel engine exhaust, acoustic noise and thermal signatures can no longer be hidden, thus become an easily detectable target. Since in most missions critical operations are located near the power generators, the signature of the generator can easily lead to the targeting of installations. Since the Future Army Capability report articulates the requirement for seamless transition between strategic and tactical operations to meet rapidly changing political and military options, better power sources are required to meet

these capabilities. Lacking advanced power sources in the battlespace could also render the CF non-interoperable with our Allies.
The general requirements for this application are:

0.1 - 100 kW power level
Silent operation
Liquid fuel operation desirable
Lightweight
Reduced thermal signature
Long life/low maintenance

f) Satellite Power

Future military operations will depend increasingly on space assets for surveillance and communications. New concepts related to the deployment of inexpensive, mass-produced and deployed satellites are emerging. Mass produced nano- and pico-satellites could be deployed in clusters of interactive satellites thereby improving survivability, reducing cost and increasing reliability. Provision of power for these small satellites will be of increasing concern.

g) Propulsion Power

Mobility, both to and on the battlefield, will be a key factor in future military operations. Fully electrically driven or engine-electric hybrid technology offers weapon platforms with increased maneuverability, survivability (active armor), firepower (advanced weapons), stealth (reduced signatures and increased deception), reduced weight and size (critical for autonomous vehicle), and improvements in system availability, integration flexibility, and cost effectiveness.

The platform features and application drive the power requirement. For land vehicles, power requirements range from 5 kW to 300 kW for a light armored vehicle, and up to 1 MW for a main battle tank. On the Navy side, a typical frigate has a total of 40-50 MW capacity and 7-8 prime movers. In a hybrid electric ship, the prime movers would be used to generate electricity, which then can be easily distributed through the electrical grid on the ship. A gas turbine would still be used for high-speed maneuvers, but for economical and silent cruising the electrical system would be used. This not only reduces life cycle costs but also reduces detectability and provides an electrical source for high power weapons. Submarines have always been hybrid electric ships because of the underwater requirement. When compared to diesel engines, fuel cell propulsion systems can provide submarines with important tactical advantages resulting from lower acoustic noise, lower structural vibration, and longer submersion duration. It can also improve the quality of life of the submariner by providing better quality air and a quieter environment. A typical submarine requires about 5 MW shaft power.

h) Central/Fixed Power

Central/fixed power represents the power needed in CF bases and wings as well as needed in deployable camps. Although at the bases and wings the power is usually provided through the local hydro companies, backup power must also be considered.

Typical power requirements are in the range from 100's of kilowatts to many megawatts.

a. Fixed infrastructures:

Examples:	RMC Kingston -	3 MW
	CFB Edmonton -	7 MW
	CFB Petawawa-	5 MW
	CFB Halifax -	14 MW

b. Deployable camps in Balkans: - 1 MW, with 1.5 MW capacity

i) Pulse Power

The requirement for pulse power is fairly new as the weapons that require it are yet under development. The energy needed for those shots is not that high, but has to be delivered in a timeframe from nano- to micro-, sometimes milliseconds. Thus the required power ranges from several tens of megawatts up to some gigawatts. Weapons with increased lethality will be developed to counter improvements in armor and the use of electronic and optical systems. Technologies that will be developed include Kinetic Energy (KE) weapons and Directed Energy (DE) Weapons. KE weapons include electric (coil and rail) guns and electro-thermal chemical propellant guns capable of firing high velocity projectiles with increased lethality. DE weapons, such as high power microwave and laser/particle beams, will become increasingly important as a means of offensive/defensive denial and deception against the use of sophisticated electronic and computer systems on the battlefield. As a result, the requirement for compact power sources with high-energy pulse capabilities will increase dramatically. RF munitions require a very compact pulsed power source based on the use of explosives.

Table 1: Classification of CF Power Source Requirements

POWER RANGE	REQUIREMENTS	DESIRED CHARACTERISTICS general	DESIRED CHARACTERISTICS detailed
Micro Power (μW – 100 mW)	Sensors/ Actuators/ Smart Structures	Microscopic scale High energy density/long endurance Environmentally friendly Energy harvesting desirable Ambient temperature	
Low Power (100 mW – 100 W)	Soldier Systems/ Integrated Wearable Power	Extremely high energy density Highly efficient Low signature Safe and maintenance-free Low life cycle costs Energy harvesting desirable	1350 Wh 1300 Wh/dm^3 5900 Wh/kg -40C logistic fuel low signature
	Digitized Battlefield	High energy density Compact/lightweight Low signature Non-polluting /low cost Long cycle life	
	Miniature Robotics	High energy density Maintenance free Low signature Reliable	> 1000 Wh/kg Low signature Logistic fuels
Medium Power (100 W – 100 kW)	Tactical Power (Mobile and Stationary)	Compact/lightweight Low fuel consumption Rugged/reliable Interoperability Ambient temperature Low Maintenance Energy harvesting desirable	
	Aerospace Power (Small Satellites)	High energy density Compact/lightweight Reliable/safe	
High Power (100 kW – 10 GW)	Vehicle Propulsion	High energy and power density Rugged/Safe Compact/lightweight Low fuel consumption Suitable for mil. environmental conditions Interoperability	
	Central Power	Low fuel consumption Low life-cycle costs Easy to use and to maintain Long MTBF, short MTTR Interoperability	
	Pulse Power	High energy Very high power density Compact Rugged	

4. STUDY METHODOLOGY:

The methodology of the study is outlined in the "Statement of Work" for PWGSC Contract # W7714-5-0915. This study was undertaken in order to update the results of a Technology Trends, Threats, Requirements and Opportunities Study of Advanced Power Sources (hereafter referred to as the T3R&O study) that was completed in 2001. This update was considered necessary because of rapid developments in the power source field and the expanded role of the CF/DND in the defence and security fields following the events of 9/11.

Because of the very wide variety of technologies that needed to be examined, the input of a relatively large number of "Technical Experts" was sought. To collect information, a questionnaire was prepared and distributed to these experts. As part of this questionnaire, the Experts were asked specifically what role nanotechnology is expected to play in the development of advanced power sources. To supplement the information collected from the Technical Experts, the contractor, March Scientific Ltd., also surveyed the various power source areas independently. This report summarizes the results of these studies. The information collected has been used to assess the Technology Readiness Levels of nine selected power source technologies.

Input from the following technical experts is gratefully acknowledged:

Batteries:	Dr. I Davidson Dr. W.A. Adams
Fuel Cells and Hydrogen:	Dr. B. Lakeman Dr. G. McLean Dr. C. Bock Dr. T. Kimmel Dr. B. Davis Dr. B. Borglum Dr. P. Sarkar
Microengines:	Mr. G. Webster
Pulse Power:	Dr. M. Kekez
Energy Harvesting:	Dr. G. Amow Dr. R. Thorne
Nuclear and Radioisotopic:	Dr. L. Bennett Dr. D. Haslip Dr. R. Nishimura

5. OVERVIEW OF POWER SOURCE TECHNOLOGIES:

5.1 Batteries:

Present Status:

In many ways, batteries represent the ideal solution for providing mobile power for the soldier. They operate at ambient temperature and over a wide temperature range, thermal and acoustic signatures are low or negligible, they are generally insensitive to orientation and are self-contained and do not require supplies of air or water. In general, other (air breathing) sources of power should only be considered when available batteries are inadequate to meet the power requirements. The importance of energy conservation and management in reducing power requirements has been discussed [11] in the context of the US Land Warrior program. In spite of these advantages, existing batteries are inadequate to meet the power requirements of many future missions. Future Soldier Systems are expected to contain a wide variety of advanced electronic technologies. Battery power is becoming a limiting factor and is creating a logistical and tactical burden.

In this section of the report we update the battery related material that was in the earlier [10] DRDC sponsored T3R&O Study.

Non-rechargeable (Primary) Batteries

Non-rechargeable lithium batteries offer the highest energy density and are in wide use in the military. The BA-5590, based on Li/SO_2 chemistry, is widely used in field radios and other portable electronics. This battery offers excellent low temperature and high rate performance. Battery safety, disposal and cost important considerations that have led to the examination and use of other battery chemistries such as $LiMnO_2$ and $Li/(CF)_x$. A summary of the characteristics of these battery types is given in Table 2. These technologies are all relatively mature. R&D efforts are expected be aimed at cost reduction through new packaging (e.g. pouch cells) and manufacturing techniques. Improvements in safety and increases in power and energy densities can also be expected.

Table 2: Properties of Selected Non-Rechargeable Batteries [10]

Cell Couple	OCV[a] (V)	NLV[b] (V)	Energy density[c] (Wh kg^{-1})	Energy density[c] (Wh dm^{-3})	Power density (cont.) (W kg^{-1})	Temperature range (^oC)	Discharge profile	D Wt (g)	Size cap (Ah)
Li/SO_2	2.9	2.75	250	400	140 650*	-50 to 70	Flat	85	7.5
Li/CF_x	3.0	2.8	360	680	14	-40 to 85	Flat	93	12
Li/MnO_2	3.4	2.8	280	580	50	-30 to 70	Sloping	105	10
$Li/SOCl_2$	3.65	3.5	290	670	105 2500*	-40 to 85	Flat	100	13

[a] Open circuit voltage [b] Nominal load voltage [c] Practical energy density of high-rate spirally wound cells. This is only a rough guide and corresponds to a moderate load. The value will vary with the load, temperature and depth of discharge.* = 1 second pulses

The use of non-rechargeable batteries can provide a logistical burden during military operations. As an example [1], "as (US) operation Iraqi Freedom opened, batteries were in very short supply, as troops in the south of Iraq used half of the projected total war requirements in only a few days. Supplies to combatants in the North of Iraq were unavailable. Forward stocks of batteries drained during the first days of the hostilities and the entire supply of the US Army was to be used up in two months, if not replenished under an emergency program. Batteries had to be air lifted from US depots to Iraq and round the clock production of new inventories had to be initiated with six manufacturers worldwide". The use of rechargeable lithium batteries for training (because of cost and availability considerations) rather than the higher energy density non-rechargeable versions often led [12] to ineffective use and premature disposal of the non-rechargeable battery during combat. For these reasons, CF policy regarding the use of non-rechargeable batteries is being reviewed. To meet Canadian Soldier System requirements, the Directorate Soldier System Project Management (DSSPM) has decided to use high energy density rechargeable batteries combined with alternate power sources (e.g. fuel cells, solar power and engine generators) for recharge in the field.

Rechargeable (Secondary) Batteries.

A comprehensive review of rechargeable battery technology has been given in the earlier T3R&O study [10]. In this section, we provide an update of this earlier material particularly as it relates to the higher energy density lithium ion and lithium polymer batteries.

A number of different chemistries have been used for the positive electrode including $LiCoO_2$, $LiNiO_2$, and $LiMn_2O_4$. The negative electrode is made from carbon or graphite material. During charge and discharge, the lithium ions can move from one electrode to the other with little disruption of the structure (i.e. intercalate) as illustrated in Figure 5. In lithium polymer cells, the electrolyte is immobilized so that it behaves like a polymer. This gives more flexibility with packaging. The performance of lithium polymer cells is similar to that of lithium ion.

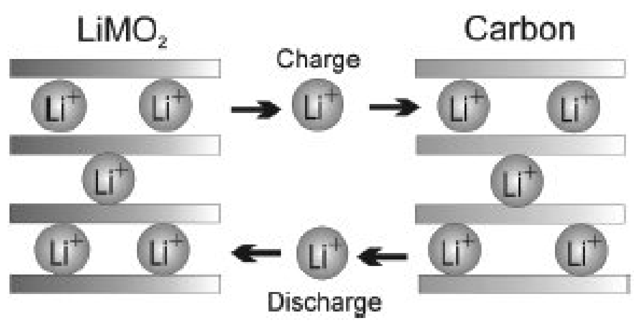

Figure 5 - Intercalation of Lithium in a Lithium Ion Battery (from [13])

Future Developments:

Even though lithium ion batteries have the best performance of any rechargeable battery and have largely replaced other battery types in commercial electronic (e.g. computer and cell phone) applications, they have a number of deficiencies that the R&D community is trying to address. This is especially true for military applications where improvements are needed in energy and power density, low temperature performance, safety and improved storage life especially at high temperatures (>55C). To meet these challenges, a large international research effort is underway, which is directed at all aspects of lithium ion chemistry. This includes the development of improved anodes [14], cathodes [13,15], and electrolytes [16]. Some specific activity includes:

Anode: At the present time, most batteries use [14] a carbon (graphite) based anode. The graphite crystal structure is built up of a lattice of carbon atoms lined up as a hexagonal mesh. This allows insertion of the lithium ions into the graphite material. The theoretical capacity of LiC_6 is 372 Ah/kg. As an alternate to graphite, there has been considerable interest in the use of tin based anodes because they have the potential [14] to store more than twice as much lithium as graphite. In this anode material, lithium is reversibly alloyed with the Sn. In theory as many as 4.4 Li atoms can be accommodated corresponding to a theoretical capacity of 781 Ah/kg. Problems with the functioning of this electrode have resulted from the large volume changes that occur during charge and discharge, which, as a result of mechanical instability, has resulted in loss of capacity and low cycle life. As described below, the use of nanostructured Sn-based anodes promises to improve cyclability as well as rate capability.

Carbon nanotubes have been investigated [17] as a replacement for graphite in lithium ion batteries. Because of the higher electrical conductivity and higher surface area of carbon nanotubes with respect to graphite, improved performance can be expected. A major disadvantage of these materials has been the high cost of these materials. Recently progress has been made in this area with the production [18] of low cost multi-wall carbon nanotubes (MWCNT).

Cathode: Many commercial lithium ion batteries use $LiCoO_2$ as the cathode material, Li_xC_6 as the anode material and a lithium ion-conducting electrolyte. Replacement of $LiCoO_2$ is desirable because this material is expensive and toxic. For this reason a number of alternate cathode materials are being investigated. Ideally, a good cathode material should have the following properties:

- high voltage
- high capacity
- reversible lithium insertion
- chemically stability
- good electrical and ionic conductivity
- a continuous voltage profile
- inexpensive and environmentally safe

A number of alternate cathode materials are being investigated including [13] $LiCo_{1-y}Ni_yO_2$, $LiNiO_2$, $LiMnO_2$, $LiMn_2O_4$, LiV_2O_5 and $LiFePO_4$. The last compound, lithium iron phosphate [19], is attractive as iron is cheaper and more environmentally friendly than cobalt, nickel or manganese. Commercial development of a lithium ion battery based on $LiFePO_4$ is reportedly [20] being carried out by A123 Systems and probably others. The impact of nanotechnology on cathode development is discussed in the following section of this report.

Electrolytes: The chemical stability of the electrolyte used in lithium ion batteries limits the choice of electrode material (hence energy density), storage life at high temperatures and low temperature performance. At the present time, a mixture of alkyl carbonates and $LiPF_6$ is commonly used as the electrolyte. A major challenge is the development of new electrolytes that will be stable enough to allow the use of higher energy density materials having theoretical open circuit voltages (OCVs) closer to 5 V, to improve low temperature conductivity, give good high temperature performance with minimum capacity loss and with improved safety (non-flammable and no thermal run away). A wide variety of solvents and salts are being investigated [16]. The development of solid electrolytes is an important area.

Several other chemistries have the potential for significantly increased energy densities. This includes Li/S, which has a theoretical energy density of 2600 Wh/kg. A major drawback to date has been short cycle life due to the migration of polysulphides through the cell. This problem is being addressed through the use of a polymer electrolyte. The system is being commercialized by Sion Power Corporation [21]. Another chemistry in which there is renewed interest is lithium/air which has a theoretical energy density of 13,000 Wh/kg. This system is being developed by PolyPlus Battery Company [22]. Aluminum/air and carbon/air systems also have high theoretical energy densities. Carbon/air operates at high temperature and would be unsuitable for low power, mobile systems.

Impact of Nanotechnology:

The use of nanomaterials is increasingly showing promise for the improvement of cathode and anode performance in lithium ion batteries. Several groups have shown that these materials have the capability for increasing the rate capability [15], low temperature performance and safety. In nanoscopic particles, the fraction of the atoms at or near the surface is much greater that with larger (microscopic) particles. This reduces the distance that Li needs to diffuse in the solid phase and, thus, greatly enhances the charge and discharge rate capability of the battery. Safety problems (thermal runaway) often occur when dendritic lithium is deposited because the lithium cannot intercalate into the anode and/or cathode fast enough. The use of nanomaterials should therefore also improve battery safety. The use of nanomaterials will also reduce volumetric changes and lattice stresses, which improves the mechanical stability of the electrodes. Some specific examples of activity in this area includes:

Anode: As mentioned above, tin based anodes are of interest because they can potentially store twice as much lithium as graphite. The mechanical stability of conventional anodes is poor however because of the large changes in volume that occurs during the alloying/dealloying process. Nanoscopic particles, on the other hand, can accommodate much more easily the structural changes that occur during cycling which results in improved mechanical stability [14].

A number of workers have examined [17] the use of carbon nanotubes as a replacement for the graphite that is used in conventional anodes. Because of higher electrical conductivity and a larger surface area, improved rate capability and low temperature performance is anticipated. One of the main stumbling blocks to date has been the high cost of these materials. Progress is being made however with cost reduction [18].

Cathode: The use of nanostructured cathode materials as a replacement for conventional materials promises to significantly improve the performance of lithium ion batteries. Recently, a number of nanostructured transition metal oxides have been prepared and their electrochemical performance evaluated. Materials studied include: LiV_2O_5 and other vanadium oxides, $LiCoO_2$, $LiMnO_2$, $LiMn_2O_4$ and $LiFePO_4$.

3-D Architectures: The present design used for lithium ion batteries is essentially two-dimensional. In recent years, it has been realized that the potential of both battery and fuel cell systems can be substantially improved through the use of 3-D architectures, which optimize power and energy density while maintaining short ionic transport distances. Work in this area is area is being carried out under a US MURI project on "Three Dimensional Architectures for Electrochemical Power Storage" and has been the subject of a recent review [23].

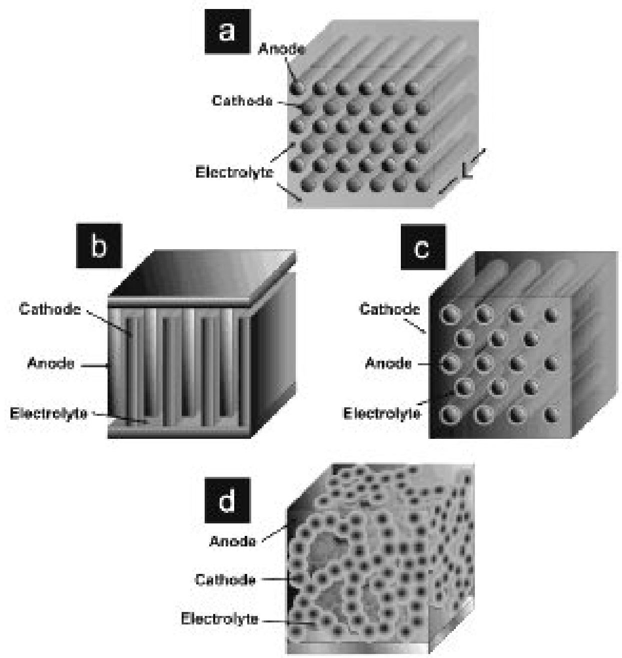

Figure 6 - Potential 3-Dimensional Battery Architectures (from [23])

Performance Projections for Rechargeable Batteries:

a) Lithium Ion Batteries

Because of their dominant position in the commercial electronics market, there is an intense R&D activity aimed at the improvement of this battery system. The following (Table 3) are the performance projections collected from experts canvassed in this study.

Table 3 - Performance Projections for Lithium Ion Batteries

Battery Parameter	Present	+ 5 Years	+ 10 Years	+ 20 Years
Energy Density - Wh/kg - Wh/l	225 475	280 550	330 650	- -
Power Density - W/kg	1500-2500	>3500	-	-

b) Metal/Air and Carbon/Air Batteries

There is renewed interest in lithium/air, aluminum/air and carbon/air batteries all of which have a potentially high energy density as shown in the projections given in Table 4. The power density of these systems is generally expected to be low so they would likely be used in a hybrid configuration to provide high energy density with some other element such as a lithium ion battery or supercapacitor meeting the peak power requirements. With lithium/air, long-term storage may be an issue because of the highly reactive nature of metallic lithium. Protective films for the protection of the lithium are being investigated.

Table 4 - Projected Characteristics of Metal/Air and Carbon/Air Batteries [11]

Battery Parameter	Lithium/Air	Aluminum/Air	Carbon/Air
Discharge Reaction	$2\,Li + H_2O + 1/2\,O_2 = 2\,LiOH$	$4\,Al + 6\,H_2O + 3\,O_2 = 4\,Al(OH)_3$	$2\,C + O_2 = CO_2$
Theoretical Voltage	3.4	2.7	1.0
Working Voltage	2.85	1.1 - 1.4	-
Theoretical Energy Density (Wh/kg)	13,000	8100	9100
Projected Energy Density (Wh/kg)	2600	1620	2400

5.2 Fuel Cells:

Introduction:

There is currently tremendous military and commercial interest in small format fuel cells as a potential replacement for rechargeable lithium batteries in a wide range of applications. Civilian applications include the replacement of lithium batteries in laptop computers and cell phones while military applications include Soldier System power, robotic systems and MEMS based sensors and actuators. Some of the potential advantages of these small format fuel cells include high energy density, low emissions, operation at or near ambient temperature, and fast and convenient refueling.

Present Status:

While most of the small format fuel cells are of the PEM type, a variety of fuel choice options are being explored. Some of the principal developments include:

Hydrogen Proton Exchange Membrane Fuel Cells (PEMFC):

Because of the intense development of hydrogen fueled PEMFCs, largely for automotive applications over the past 20 years by companies such as Ballard Power, PEM fuel cell technology is at an advanced state of development. The use of hydrogen, either stored as a high-pressure gas or in a metal hydride, simplifies system design. For a portable military system, which must operate over a wide range of environmental conditions and have high energy and power density, the system is surprisingly complex. Fuel cell subsystems are needed to control water balance, stack temperature, the feed of fuel and oxidant and system start-up and shut down. With a PEM fuel cell, the membrane humidification must be carefully controlled to prevent drying of the membrane so that membrane conductivity is maintained but also so that cathode flooding does not occur. Special control of water balance is needed during system shutdown to prevent damage from freezing if the system is exposed to low temperatures. The design [11] of Ball Aerospace's PPS-50 hydrogen fueled potable PEM fuel cell system provides a good illustration of the extensive control that is required. The microprocessor-controlled system manages hydrogen and oxidant delivery, water removal and system temperature. The Ball Aerospace PPS-50 was reported [11] to weigh 2.9 kg and occupy 4.26 l without fuel.

Table 5 - Energy Densities of Various Hydrogen Storage Technologies [11]

Hydrogen Source	Gravimetric Energy Density		Source Type
	Theoretical Wh/kg	Practical Wh/kg	
HP Hydrogen (2%)	653	312	Passive
Metal Hydride(1.5%)	490	234	Active
LiH - own water	2516	1199	Passive
LiH - FC water	8283	3949	Active
CaH_2 - own water	1699	810	Passive
CaH_2 - FC water	3105	1480	Active
$NaBH_4$ - own water	2386	1114	Active
$NaBH_4$ - FC water	8170	3897	Active
NH_3	5753	2194	Active
NH_3BH_3	6406	2443	Active
Reformed Methanol - own water	3948	1600	Active
Reformed Methanol - FC water	6168	2353	Active

The choice of hydrogen source has a major impact on the overall complexity and energy density of the PEMFC. Two classes of hydrogen source can be identified: hydrogen storage or hydrogen generation sources. Within each class they can be further classified as either passive or active, where an active source requires fuel cell resources (e.g. water, heat or electrical power) for operation. A summary of some of the major hydrogen sources being considered for military application together with theoretical and practical energy densities is given in Table 5.

Hydrogen can be stored either as a high-pressure gas or metal hydride. Storage of hydrogen as a high-pressure gas provides a very simple system. It is passive, is essentially independent of environmental conditions, and follows load changes easily. Large (e.g. automotive) systems have achieved [24] >5 weight percent hydrogen storage when high pressure and composite vessels are used. With smaller systems, the storage efficiency is much lower and, in the size needed for the Soldier System, 2 weight percent hydrogen is more realistic [25]. At 2 weight percent, the Ball Aerospace PPS-50 fuel cell would have a total system energy density of 177 Wh/kg for a 24 hour mission or 249 Wh/kg for a 72 hour mission. This calculation assumes [11] an overall fuel cell efficiency of 47.7%. This energy density is not high enough to meet the Soldier System requirements.

Reversible metal hydrides are also being considered [25] for hydrogen storage. While the gravimetric energy density is about the same or slightly lower than that of compressed hydrogen, the volumetric energy density is larger. Metal hydrides operating at room temperature can store approximately 1.5 weight percent hydrogen while those operating at elevated temperature can release more that 4 weight percent. Cylinder pressures are much lower than with high-pressure gas storage and are thus inherently safer. Metal hydride storage systems require heat from the fuel cell to release the hydrogen from the alloy. This may cause problems with operation over a wide temperature range (i.e. at low temperatures). As with high-pressure gas storage, the storage efficiency decreases as the size of the storage system decreases. As with high pressure gas storage, the energy density of metal hydride storage is not high enough to meet the Soldier System requirements.

Several methods for generating hydrogen have been considered. These include the hydrolysis of chemical hydrides such as sodium borohydride ($NaBH_4$), the thermal decomposition of hydrogen rich compounds such as ammonia or ammonia borane or reformation of fuels such as methanol. All of these methods have potential for the development of hydrogen sources having a much higher gravimetric energy density than either compressed hydrogen or metal hydrides. The gain in energy density comes at the expense of system complexity however. The development of a hydrogen source based on the hydrolysis of $NaBH_4$ has been undertaken [26] by Millennium Cell Inc. The hydrogen generation process, illustrated in Figure 7, is quite complex. In this system, a slurry of $NaBH_4$ and water is passed over a catalyst, which decomposes the NaBH4 to give hydrogen, and (hydrated) sodium borate, which needs to be collected and stored. The overall energy density of the system will depend on the concentration of $NaBH_4$ in the slurry and the collection and use of product water from the fuel cell for use in the hydrogen generation process. Production of $NaBH_4$ is energy intensive and hence expensive.

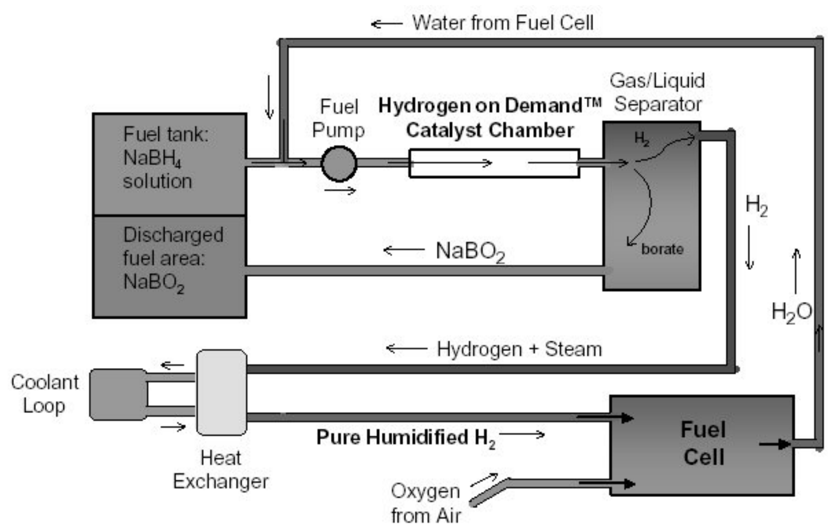

Figure 7 - Hydrogen Generation Using Sodium Borohydride (from [26])

The thermal decomposition of hydrogen rich compounds such as ammonia or ammonia borane can also provide a high energy density source (17.6 and 19.6 weight percent respectively). The thermal cracking of these compounds must be carried out at elevated temperature (120 - 300°C), which requires some energy either from the fuel cell or from the combustion of hydrogen. The cracking of ammonia only produces hydrogen and nitrogen. The nitrogen is gaseous and inert and is easily handled in the fuel cell. Residual ammonia in the hydrogen stream must be removed or it will react with the protons in the membrane resulting in low membrane conductivity.

Ammonia borane is a white crystalline solid. Decomposition of this solid also produces boron nitride, a solid material, so material handling is more complex that with ammonia. It has recently been reported [27] that incorporation of ammonia borane in mesoporous silica facilitates the release of hydrogen. Ammonia borane is produced in Canada by BoroScience Canada.

The reformation of oxygenated organic fuels such as methanol occurs relatively easily and at relatively low temperatures. Methanol is also an easily handled and low cost liquid. The reformation process is relatively complex. Water is required in reforming to shift the carbon monoxide that is formed to CO_2. This is usually done in a two-stage process through the use of first a high temperature shift reactor and then a low temperature shift reactor. To prevent poisoning of the anode catalyst, it is then usually necessary to further reduce CO levels to the ppm level using a PROX reactor. These reactors will add size, weight and complexity to the fuel cell system. Ultracell have, however, been able to develop [28] a compact methanol reformer suitable for a high energy density 25 Watt system.

Companies involved in the development and demonstration of hydrogen fueled PEMFCs include Ball Aerospace, Protonex, Ultracell, Angstrom Power, Hydrogenics, Neah Power Systems and DCH/Enable. A brief summary of these systems is given below:

1. Ball Aerospace PPS-50

The Ball Aerospace PPS-50 PEMFC is electronically controlled. The control system is designed to manage fuel and oxidant (air) flow, temperature and water balance in the fuel cell stack. The weight of the system is [11] 2.9 kg and its volume is 4.26 L. A chemical hydride was apparently used as the fuel although detailed information on fuel source was not available. It was reported that " the demonstrated specific energy is 540 Wh/kg when running a 6% by weight hydrogen solution at 50 W for 72 hours (3,600 Wh at 6.6 kg). A 24 hour mission at 50 Watts would have specific energy of 286 Wh/kg". Ball Aerospace & Technologies Corp. shipped eight portable power systems (PPS) to its military customers. The technology readiness level of these units was given [11] as TRL=7.

2. Protonex Technology Corporation/Millenium Cell [11]

Protonex Technology Corporation is working on a U.S. Air Force Research Laboratory, Dual Use Science and Technology (DUST) contract to develop a soldier portable 30 Watt power source. Millenium Cell is providing a borohydride fuel source for the 30 W PEMFC based on their patented technology. In March 2005 the Protonex/Millennium Cell team delivered a prototype 30-watt fuel cell power system (P1) to the Air Force. The system demonstrates a 50% weight savings for a three (3) day mission over the conventional primary batteries a soldier carries today. This contract is expected "to culminate with the delivery of a second prototype with a Technical Readiness Level (TRL) of 6 -7 and energy density greater than 425 – 500 Wh/ kg by late 2005".

The next generation of Protonex portable soldier power, P2, should further reduce the weight to only 33% of the weight of existing battery solutions. Protonex anticipates this product going into military field trials in 2006.

3. UltraCell [28]

UltraCell is developing [28] a 25-Watt portable micro fuel cell (Model # XX25) for the military market. The system weight is 1 kg and a 550 cc fuel cartridge provides 490 Wh. For a 72-hour mission, three fuel cartridges are needed and the total system weight is 2.9 kg. In this application, an energy density of 500 Wh/kg is achieved. The system is currently undergoing field tests by the US Military. The current TRL is about 5. In June 2006, the company received a contract from the US Army Communications-Electronics Research, Development and Engineering Center (CERDEC) to accelerate the development of the XX25 for use as a Soldier System power source.

4. Angstrom Power:

Angstrom Power has developed a fuel cell technology using a unique architecture that packs a large amount of surface area into a small volume (Figure 8). This architecture positions many series and parallel connected unit fuel cells in a thin layer orthogonal to the planes in which reactants flow thus providing high reliability [29]. Angstrom is developing this technology primarily for the consumer electronics market. Their technology produces compact fuel cell systems that can operate at ambient conditions without the "balance-of-plant" (BOP) such as pumps and fans typically required by conventional fuel cell systems. While this simplified control system may work well for consumer electronic applications, operation of such a system over the wide range of environmental conditions needed for most military applications would probably be difficult.

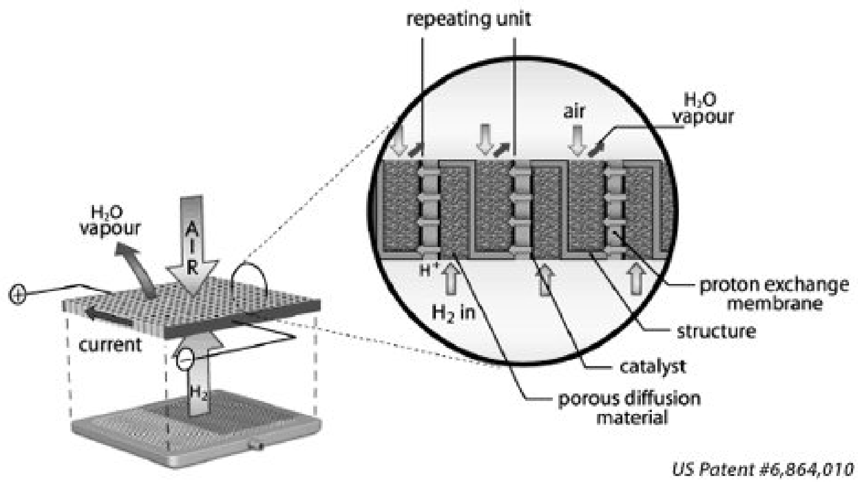

Figure 8 - Angstrom Power's Micro Fuel Cell Technology [29]

Angstrom Power fuel cells run off hydrogen stored as metal hydride and takes oxygen from the air. Angstrom power has developed [29] and is marketing a portable fuel cell power source for charging electronic devices. The unit includes an integrated metal hydride fuel source that can be recharged at a refueling station. As developed, the 2 W unit can provide 12 Wh of energy and has a gravimetric energy density of about 35 Wh/kg. Projected [30] performance characteristics are much higher and are summarized in Table 6.

5. Hydrogenics

Hydrogenics Corporation is developing a self-contained regenerative fuel cell power system that will be used to provide auxiliary power for a U.S. Army Stryker Light Armoured Vehicle (LAV). Radian Inc. is responsible for the on-board integration of the auxiliary power system and its testing and validation. This is a collaborative government project with Radian being contracted by the United States Army (TACOM/TARDEC), and Hydrogenics contracted by Defence R&D Canada under the Defence Industrial Research program. The regenerative power system, an integrated configuration of Hydrogenics' PEMFC and electrolyser technologies, is designed to extend the silent watch capabilities of the Stryker LAV. As part of the 12-month project, the LAV will be tested and demonstrated for the U.S. Army.

The electrolyzer component of the on-board regenerative system produces hydrogen which is then stored and subsequently used, on-demand, by the fuel cell component.

6. DoD Residential PEM Fuel Cell Demonstration Program

Under this program, DoD has installed a total of 85 PEM fuel cell installations that were manufactured by 4 companies - Plug Power, ReliOn, Nuvera and IdaTech. The PEMFCs developed by ReliOn operated on hydrogen whereas the other systems operated on reformed natural gas or propane. The systems were used to produce both electrical and thermal energy. A summary of the results of this demonstration program has recently been published [31]. A total of more than 300,000 operating hours was accumulated on the 85 units. The overall availability of the fuel cells was near 90% and the electrical and overall efficiencies were roughly 24% and 28% respectively.

Direct Methanol Fuel Cells (DMFC):

To avoid problems with hydrogen storage and to achieve potentially higher energy densities, a water/methanol mixture is used as the fuel in a DMFC rather than hydrogen. There has been worldwide commercial interest in DMFCs as a replacement for lithium-ion batteries in cell phones and laptop computers and military interest as a high energy density power source for the Soldier System. Companies involved in commercial development of DMFCs include Motorola, MTI Micro, Toshiba and Samsung. Under the DARPA Palm Power program, both Ball Aerospace and Mesoscopic Systems have undertaken the development of 20 W systems. System energy densities of ~ 600 Wh/kg (approximately 3 times that of lithium ion) have been forecast.

One of the most pressing problems [32] with the direct methanol fuel cells is that the rate of reaction is slow and the cells are subject to poisoning from reaction intermediates at the anode and slow degradation of the cathode due to platinum oxidation at high cathode potentials. This manifests itself as a high activation over-voltage at both the anode and cathode. The result is a low overall cell operating voltage, and thus a low efficiency. To try to overcome this problem, very high loadings of a platinum/ruthenium catalyst are normally used at the anode. Ruthenium cross-over has also be identified as a degradation mechanism [32].

Fuel crossover (diffusion of methanol from the anode to the cathode), which results in reduction of cathode voltage and fuel inefficiency, is also a major problem. To try to overcome this problem, new membranes that are less permeable to methanol are under development [33]. Water management is also a serious issue with DMFCs. Flooding of the cathode must be prevented and product water needs to be retrieved for mixture with the methanol to achieve a high overall energy density. Complex sub-systems must be used to collect and store the product water and then mix this water with the pure methanol that is used as the fuel to obtain methanol concentrations that are optimized for the membrane and DMFC stack (with a Nafion membrane this is generally in the range of 1 -2 molar). MTI Micro has reported the development of a passive water recovery system for the low power DMFCs that they are developing.

Despite these problems, the easy availability, ease of storage and handling, high energy density and safety of methanol fuel make it so attractive that development effort to solve these problems is intense and commercialization of DMFCs for certain low power applications seem likely in the near future.

Direct Formic Acid Fuel Cells (DFAFC):

As an alternative to DMFCs, direct formic acid fuel cells have been proposed [34]. While formic acid has a lower energy density than methanol (2086 Wh/l compared with 4690 Wh/l), many of the problems associated with DMFCs are alleviated. In particular fuel crossover is reduced which allows a much higher fuel concentration to be used. The electrooxidation of formic acid is easier, which allows higher power densities to be achieved. In addition, it performs at a lower operating temperature, uses lower cost catalysts, and, due to its chemistry, it requires fewer balance-of-plant components. For small systems, the higher power density of the fuel cell stack can result in higher overall system energy density even though the fuel energy density is lower. While less severe that with DMFCs, the slow accumulation of CO at the catalyst causes degradation of performance with time [35]. Periodic pulsing of the cell potential to raise the anode potential has been shown [35] to be effective in restoring cell performance.

Development of DFAFCs is being undertaken by Tekion Inc. who are located in Burnaby, B.C. This company has recently signed a development agreement with Motorola for the development of micro fuel cells for mobile commercial products (e.g., cell phones). The company has also recently signed an agreement with BASF to develop a formic acid formulation for fuel cell use as well as the development of applicable codes and standards associated with the transport and use of formic acid in fuel cells. According to information on the Tekion web site " Tekion also intends to ruggedize fuel cell products for military applications". It can be anticipated that development of a portable DFAFC for military use over a wide range of environmental conditions will require the development of a more complex fuel cell control system than will be needed for small commercial systems that will operate near room temperature.

Solid Oxide Fuel Cells:

There is considerable interest in the development of SOFC technology in Canada. The Alberta Research Council (ARC) is developing a high power density solid oxide fuel cell (HPD-SOFC). This technology is based on a microtubular design that is resistant to thermal shock allowing rapid start-up and shutdown. The technology is adaptable to a wide range of power sizes. At present, SOFCs are at an early stage of development (TRL 2 to 4). ARC is using an electrophoretic deposition (EPD) based single cell manufacturing process and several aspects of the stack and hotbox design have been patented. ARC is collaborating with the University of Alberta, University of Calgary, the Fuel Cell Centre at Kingston (RMC, Queen's University), the National Research Council's Institutes for Chemical Process and Environmental Technology (ICPET) and for Fuel Cell Innovation (IFCI) and Global Thermoelectric Inc. Adaptive Materials Inc., in the US, is developing a similar microtubular SOFC technology [11].

Some of the key technology issues that need to be addressed include:

> **Cell technology:** Cells need to be able to withstand both an oxidizing and reducing atmosphere. The commonly used yttria stabilized zirconia (YSZ)/Ni anode-supported SOFC fails once its anode is exposed to an oxidizing atmosphere. The best potential candidate to meet this requirement is a porous-electrolyte-supported (PES) cell. This means that if there is a leak in the stack or in the cell, then it is not going to damage the cell. Thin PES cells will also have a high thermal shock resistance i.e., they can be thermally cycled rapidly without damage. An improvement in the electrochemical performance of the cells is also required. The probability of success is estimated to be high (>80%).

Sulphur/Impurity Tolerant Anode: Conventional anodes contain nickel but it readily reacts with H_2S forming nickel sulphide. Since H_2S is common in hydrocarbon fuels, a sulphur tolerant anode will help with the commercialization of SOFCs. Another problem with Ni-based anodes is coke formation. Both problems are technically difficult. The probability of success for achieving sulphur tolerance is estimated to be 60% while achievement of coking tolerance is estimated at 80%.

Active Cathode: The cathode is one of the major sources of performance loss in SOFC. Cathode performance can be improved by improving the microstructure as well as by developing new materials. Nanotechnology and low temperature operation can provide a better microstructure for the cathode materials. One important criterion is that the cathode should not be chemically reacting with the electrolyte. Cathode materials will play a vital role in lowering the operating temperature of SOFC. Thin cerium gadolinium oxide (CGO)-based electrolyte has an acceptable electrical resistance at ~400^{o}C. Active cathode and anode materials are needed for operation at 400^{o}C. The probability of success is estimated to be >70%.

Current Collector: Improvements in current collector design and materials are needed to improve life and reduce cost. Cathode current collectors need to be oxidation resistant. Lowering the cell operation temperature will widen the choice of materials. With pure hydrogen as the fuel, Ni or Cu can be used as a current collector but in impure sulphur-containing atmospheres other sulphur resistant anode materials are needed. The probability of success is estimated to be ~70% if operating temperature is >800^{o}C and ~ 80% if operating temperature is lowered to ≤600^{o}C.

Stack Design & Performance: Compact high power density stack designs need to be developed. In SOFC devices, the stack is the key component. Stack design should be such that automation can be implemented. Single cell performance must not be reduced when they are in a stack. Sealing of the stack needs to be simplified. The probability of success is estimated to be >80%.

Thermal Integration and Control System: Proper thermal integration of all components of the SOFC device is important to achieve high overall efficiency and to reduce system size. Modelling and designing work in this area is important. Dynamic control system will all play a vital role in the effective use of fuel cells.

SOFC devices hold high potential for high power density, (power and/or mass-volume advantages vs. competing technologies), tolerance for fuel variation, robust construction, etc. However, the technology also requires careful thermal design, to minimize thermal signatures used by target acquisition systems, etc. One of the major advantages of SOFC technology is the ability to operate on logistical fuels. Tolerance of the anode to sulphur impurities is an issue, which will either require fuel clean up prior to use or the development of a sulphur tolerant anode catalyst. Conventional SOFC systems also do not thermally cycle or load follow very effectively, though this is less of an issue for the ARC technology. For portable applications, SOFCs will always need to be a hybrid with batteries. The purpose of the battery is to provide power during start up and to meet high power transients. Key issues relate to the improvement of single cell performance (power density), thermal cycling and cost. On the stack side, suitable assembly and sealing techniques need to be developed.

Future Developments:

An innovative approach (Figure 9) toward solving the problem of low power density is being developed by CMR Fuel Cells in the UK and jointly with Mesoscopic Systems in the US. In a conventional PEM fuel cell system, fuels and oxidants are distributed to each cell using flow-field plates. In a conventional stack, the plates account for around 90% of the volume and weight, one third of material costs and up to half of the possible cell area. In the CMR fuel cell, a mixture of fuel and oxidant flows through a fully porous anode-electrolyte-cathode assembly eliminating the need for flow-field plates. Selective catalysts are used at the anode and cathode of the cell. These developments offer the possibility to reduce the complexity, size, and costs of fuel cells and to raise stack power densities significantly.

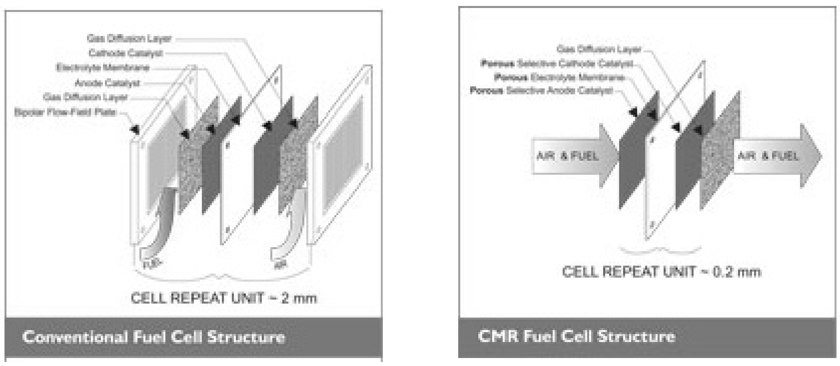

Figure 9 - A Compact Mixed Reactor (CMR) Direct Methanol Fuel Cell Design [36]

An alternative approach (Figure 10) that also promises to solve some of the problems associated with conventional DMFCs is the Laminar Flow Fuel Cell (LFFC®) that is being developed by INI Power Systems, Inc. In this concept, advantage is taken of the laminar flow properties of liquids within microfluidic channels. By this means, two or more fluids can flow in parallel and in contact yet remain discrete with little to no mixing between them. When fluids contain an electrolyte, ionic contact is established at the interface creating an electrochemical cell with full ionic conductivity between the electrodes. In the LFFC, the cell is configured so that a layer of electrolyte containing the fuel (methanol) flows adjacent to the anode and a layer containing oxygen flows adjacent to the cathode. This design provides an overall dynamic system where flowing liquids create a dynamic system that is adaptable to a wide range of environmental conditions, flexible in operation and linearly scalable to larger or smaller sizes. A disadvantage of this and the CMR system may be the use of a common electrolyte, which will result in parasitic loss due to intercell shorting. For small DMFCs containing a relatively small number of cells these losses may not be large however.

As mentioned earlier, the low power output of DMFCs is related to the fact that the rate of reaction is slow and the cells are subject to poisoning from reaction intermediates at the anode. This manifests itself as a high activation over-voltage at the anode. The result is a low overall cell operating voltage, and thus a low efficiency. Early work by Bockris (2) demonstrated that poisonous adsorbates could be electrochemically removed in situ by short duration, high-current pulses. The utility of this approach to methanol oxidation was demonstrated by Fedkiw et al who showed that Pt can be electrochemically cleaned of surface adsorbates formed from methanol electrooxidation.. The application of short duration, high-current pulses to a PEM DMFC should, in principle, provide an anode surface of high-catalytic activity on average over the periodic-pulse cycle. Pulsed-potential control of a single-cell has been recently reported to effect enhanced performance of a PEM DMFC (4). The US Army has recently issued [37] a call for proposals under the SBIR program for a "Compact Direct Methanol Fuel Cell Power System Using Pulsed Electrical Control" to investigate the utility of this approach.

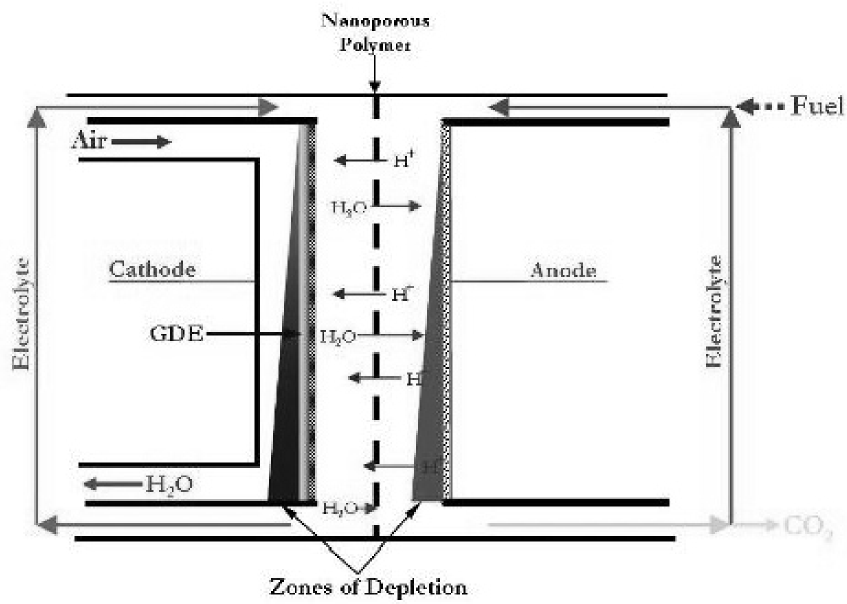

Figure 10 - A Laminar Flow Direct Methanol Fuel Cell [38]

Potential Impact of Nanotechnology:

One of the major problems hindering the development of DMFCs is that the rate of reaction is slow and the cells are subject to poisoning from reaction intermediates at the anode and slow degradation of the cathode due to platinum oxidation at high cathode potentials. This manifests itself as a high activation over-voltage at both the anode and cathode. The result is a low overall cell operating voltage, and thus a low efficiency. Development of new materials and synthetic methods that allow electrodes to be built using 3-D architectures has the potential to dramatically enhance power output by increasing electrode surface area. Neah Power Systems is using an innovative approach based upon silicon architecture. Their design (Figure 11) is expected to substantially increase the electrode surface area thus enabling much higher power densities.

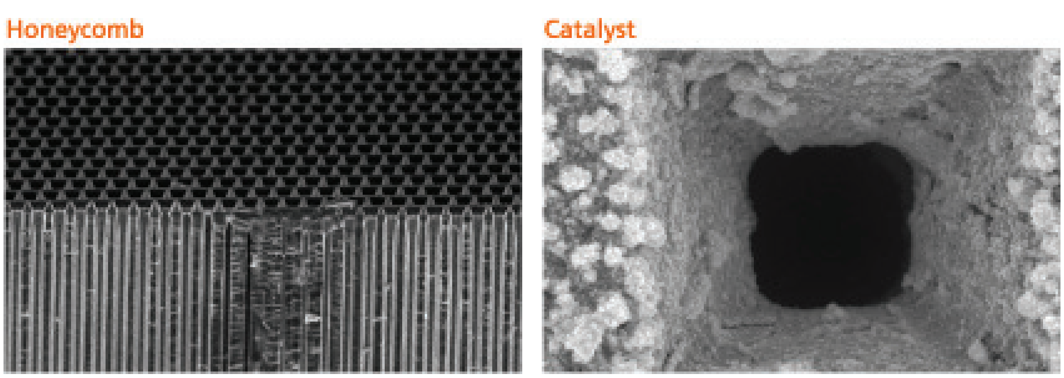

Figure 11 - Silicon Nanostructured Electrode Developed by Neah Power Systems [38]

Performance Projections for Fuel Cells:

Metal Hydride/PEM Fuel Cells

Table 6 gives performance projections for small (< 5 W) PEMFCs using metal hydrides for storage. The increase in performance primarily reflects projected improvements in hydrogen storage technology. A more complex balance-of-plant will probably be required to extend the operating range of the fuel cell to temperatures below 0°C.

Table 6 - Performance Projections for Metal Hydride/PEM Fuel Cells [30]

Fuel Cell Parameter	Present	+ 1 year	+ 3 years	+ 10 years
Energy Density - Wh/kg Wh/l	100 400	140 500	225 600	300 1000
Power Density - W/kg W/l	400 1500			
Temperature - startup operate	0 10° to 40°C			-20°C -20° to 50°C
Humidity Range	10 to 90%			

Direct Methanol and Chemical Hydride PEM Fuel Cells:

The performance of small (~ 20 W/ 72 hours) direct methanol and chemical hydride fueled PEM fuel cells is projected to be about the same. The power density for the fuel cell stack using hydrogen is expected to be considerably (~ 3 to 4 times) higher than for a stack using methanol; however the more complicated fuel processing system that will be needed to produce hydrogen from a chemical hydride such as sodium borohydride will offset this benefit. Other factors such as the logistics of supplying fuel in the field, cost and the need for disposal/recycling of chemical byproducts will ultimately influence fuel choice.

Table 7 - Projected Energy Density of Small DMFC and Chemical Hydride PEM Fuel Cells

Fuel Cell Parameter	+ 5 Years	+ 10 Years
Energy Density, Wh/kg	600	800

Solid Oxide Fuel Cells

Table 8 gives performance projections for solid oxide fuel cells. The projections are primarily for small portable military units and have been provided by the Alberta Research Council [39].

Table 8 - Performance Projections for Solid Oxide Fuel Cells

Fuel Cell Parameter	Present	+ 5 Years	+10 Years	+20 Years
Energy Density - Wh/kg 20 Watt/3 Day 50 Watt/3 Day		 700 750		
Power Density W/l		100 - 250	500 - 1000	>1000
Operating Temperature	-20C - + 60C	-50C - +60C		
Power Sizes	20W - 100 kW	250 mW - <1 MW	10 mW - 1 MW	1 mW - 10 MW
System Efficiency(%) Small Large	 15-20 35-40	 25-30 >40	 ~35 >40	 ~40 >40
Fuel Utilization (%) Small Large	 50-60 70-80	 60-70 ~80	 ~80 ~85	 >80 ~85

5.3 Microengines

Present Status:

The power and energy demands [11] of future Soldier Systems are rapidly exceeding the existing and projected energy densities of batteries. For future Soldier System requirements, power sources that can use hydrogen or hydrocarbon-based fuels that have very high energy density (Table 9) are attractive. Small engines are attractive because they offer the possibility of being able to use military fuels (such as JP-8). Potential disadvantages of using engines for the provision of portable power include difficulty in starting, thermal and acoustic signature, vibration, and a hazardous exhaust (CO poisoning). Various engine options were investigated in the US National Academy of Science study on "Energy-Efficient Technologies for the Dismounted Soldier" [40]. In this study, integrated microturboalternators were identified as being especially attractive because of their very high energy density in comparison with other engine options (Table 10). From this Table, it is seen that a 50 W microturboalternator could weigh as little as 1 gram and occupy only a few cubic centimeters.

Table 9 - Specific Energies of Various Fuels

Fuel	Specific Energy (kWh/kg)
Hydrogen	33.3
Methanol	5.5
Propane	12.8
Gasoline	12.2
Diesel	11.9

Development of a silicon-based microturbine has been undertaken by MIT [41]. The goal of this program has been the development of a hydrocarbon-fueled turbine, fully integrated with an electrical generator, using silicon micromachining techniques. The key component of the engine (Figure 12) is a free spinning (> 10 Mrpm) silicon disk that functions as compressor, turbine and generator rotor. The combustion chamber, fluidic plumbing, and generator stator components are all built into the layers of silicon that surround the rotor. Considerable progress has been made on the development of the microturbine. A recent review of this progress has given by Epstein [41].

Table 10 - Weight Comparison for 50 W Engine Generators [11]

System	Weight of Base Unit (g)		Type of Fuel	Fuel Consumption (g/Wh)	Availability
	Engine	Generator			
Spark Ignition	450	100	Methanol or propane	0.73	Near term
Steam Turbine	100	25	multifuel	0.6	+ 10 Years
MEMS Turboalternator	1	included	Hydrogen or JP-8	0.28 0.42	+ 20 Years

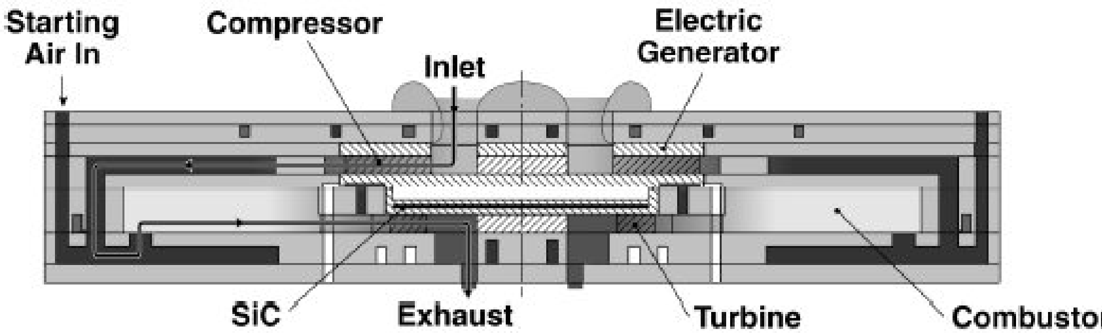

Figure 12 - MIT Designed MEMS Turbogenerator [41]

There are a number of technical issues that need to be addressed before a practical system MEMS microturboalternator can be developed. To be efficient, the MEMS turbine must operate at about 800°C, which is above the temperature that silicon can stand for long-term use. There is thus the need for the development of techniques for micromachining higher temperature materials such as SiC or SiN. While certain components (micro compressor and gas bearings) of the microturbine have been successfully developed and tested, to date self-sustained operation (i.e. net power production) has not been demonstrated.

In addition to the MIT effort, a number of other efforts have been initiated internationally aimed at the development of small microturbine engine generators in the 10 to 200 W range. Some of these efforts include Honda, IHI and the University of Tokyo in Japan, ONERA in France and the Singapore Institute of Manufacturing. Canadian expertise in this area is quite limited.
Prof. Luc Frechette at the University of Sherbrooke previously worked with the MIT group. The Canadian Microelectronic Centre in Alberta has micromachining capability.

Future Directions:

As mentioned above, to date no group has demonstrated a working microturbine at the scale being discussed. While certain elements of the micro turbine have been developed and demonstrated (turbine, bearings and hydrogen combustor) work is still needed [41] to improve aerodynamic performance, hydrocarbon combustors, thermal isolation, high temperature materials, bearings and electric generators. A major problem with the design of microengines is that they cannot be reworked when changes are required. Whenever a change is needed, the engine must be rebuilt from scratch, which is a very expensive and time-consuming process. While numerical modeling tools are available for the optimization of large gas turbine engines, these tools are inadequate at the microscale. The development of new numerical tools is needed to speed up microturbine development.

Impact of Nanotechnology:

This technology is based on silicon/silicon carbide micromachining technology. Nanotechnology may also play a part in the development of new high temperature materials.

Performance Projections for Micro Engines:

Portable microengine systems have potential as a high energy density power source to meet the requirements of the Soldier System. To achieve this a fuel-to-electrical energy conversion efficiency of only 5 - 10% is needed. Because of the very low weight of the engine itself, the weight of the power source will be essentially dictated by the theoretical fuel energy density and the conversion efficiency. Figure 13 shows a concept [41] drawing of a small engine packaged to meet the requirements of the Soldier System.

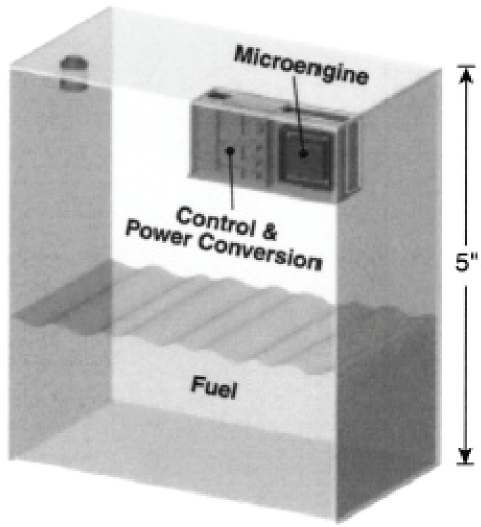

Figure 13 - Concept of a MEMS Turbogenerator Packaged as a Military Battery [41]

Performance projections for engines operating on various fuels are given in Table 11. Although hydrogen has a very high theoretical energy density, the low energy density of stored hydrogen coupled with the low conversion efficiency make hydrogen unsuitable as a fuel for this application.

Table 11 - Projected Energy Density of Portable, Microengine Power Sources

Energy Source	Theoretical Energy Density (Wh/kg)	Practical Energy Density (Wh/kg)	
		Engine Efficiency = 5%	Engine Efficiency = 10%
Hydrogen (2%)	660	33	66
Hydrogen (6%)	1980	99	198
Methanol	6200	310	620
Diesel (JP-8)	13200	660	1320

5.4 Pulse Power

Present Status:

A wide range of emerging military applications requires very high pulses of power for short duration. Some of these applications include: high power microwave (HPM) and ultra wide band (UWB) weapons, electromagnetic (rail and electrothermal chemical (ETC)) guns, electric armour for military vehicles, non-lethal weapons, burst communications and RF munitions. Civilian applications include expendable x-ray and neutron sources for non-destructive testing, destruction of biological waste, and manufacturing processes requiring high peak currents such as metal forming. The pulse power technology needed varies widely according to the power requirement (peak power, pulse duration, total energy and repetition rate) of the application as well as the particular platform (ship, aircraft, missile, munition etc) that must carry the device.

The general architecture of a pulse power source, illustrated in Figure 11, consists of a prime power source that meets the average power requirement, an intermediate storage device for rapid recharge, a high power storage device, a fast switch and the load (e.g. HPM source). In any given application, some of these elements may be missing or combined. In general, it can be said that advances in technology are needed to meet that many of the demands for the production of compact, portable pulsed power systems. The existing technology used for laboratory demonstration is generally inadequate. Some particular areas requiring development [42] include: high dielectric constant/high breakdown voltage materials for the construction of capacitors, electromagnetic modelling tools, fast switches, and thermal management especially in devices with high repetition rate. For very compact devices, there is interest [43] in explosively driven devices.

To meet the demands of these applications, the US have initiated large programs in their military and National laboratories. The Philips Laboratory in Albuquerque is known to be a leader in this field. In general, however, very few details of these programs are available because of the highly classified nature of the programs. To provide academic support for these activities, the US Airforce Office of Scientific Research supports [44] a Multidisciplinary University Research Initiative (MURI) project on Compact, Portable Pulse Power. More than 70 researchers are listed in the directory for this MURI project. Other countries are also believed to be active in this area.

The military technology areas described are, in general, highly classified. In order to properly assess the threat that these technologies pose to future CF operations, it is suggested that conduct of research in this area is important.

Future Directions:

The following outlines some of the future directions for the various elements of a pulse power system as illustrated in Figure 14.

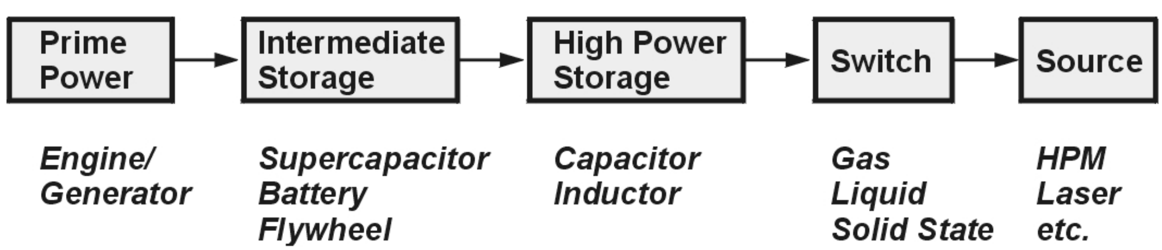

Figure 14 - Elements of a Pulse Power System

Prime Power: In the short term it is likely that prime power will be supplied by military engines combined with permanent magnet excited generators. In the future, the prime power requirements could be met using fuel cells. PEMFC are potentially attractive because of their signatures (IR, acoustic, exhaust). Fuel logistics will be important so generation of hydrogen from a common fuel such as JP-8 will be important.

Intermediate Storage: Several options are available for intermediate storage including high power batteries, supercapacitors and magnetodynamic (flywheel) storage. Improvement in the power density of both batteries and supercapacitors is desirable. As discussed below, introduction of nanomaterials in both batteries and supercapacitors promises to significantly improve rate capability. Flywheel storage is relatively mature and can provide relatively high power and energy densities. Enough energy can be stored in a flywheel for several shots of an electric weapon (e.g., an ETC gun) or to recharge the pulse power supply for the weapon.

High Power Storage: The high power storage element contains relatively little energy but can provide a high power output to meet the requirements of the device. Effort is required to improve the energy and power density of capacitors so that their size can be reduced to meet the requirements of compact power production. Development of new materials combining high dielectric constant and high breakdown strength is required.

Explosively Driven Pulsed Power Systems: Explosively driven pulsed power systems are devices that convert the chemical energy of high explosives or propellants into electrical power. Based on previous research, the best candidate for converting the chemical energy of the explosive into electrical energy is the Helical Magnetocumulative Generator (HMCG), which is also called a Helical Flux Compression Generator (HFCG). Recent research has established that when the diameter of these generators decreases below about 2 inches, they produce no current or energy gain. Improvement of the performance of small MCGs has been the subject of a recent US SBIR project [45].

Impact of Nanomaterials:

The use of nanomaterial promises to improve the characteristics of various elements needed for the successful development of compact pulse power. Some examples are as follows:

Capacitors: The maximum stored energy of a capacitor is related to the permittivity and breakdown strength of the dielectric material. In a recent study of TiO_2 as a dielectric for capacitor use , the effect of material density, grain size, and defect chemistry of the dielectrics has been examined. In this study it was found that nano-sized materials exhibit a high grain boundary area-to-volume ratio and a lower concentration of impurities within the grain boundaries. Figure 15 compares [42] the breakdown strength (BDS) of nanostructured TiO_2 and coarse- grained TiO_2. As can be seen in this figure, the nanostructured TiO_2 shows a higher BDS (1096 kV/cm) compared with the coarse-grained TiO_2, (550 kV/cm). In addition, the nanostructured material showed less variability.

Battery: The use of nanomaterials is showing promise for the improvement of cathode and anode performance in lithium ion batteries. Several groups have shown that these materials have the capability for increasing the rate capability [15], low temperature performance and safety. In nanoscopic particles, the fraction of the atoms at or near the surface is much greater that with larger (microscopic) particles. This reduces the distance that Li needs to diffuse in the solid phase and, thus, greatly enhances the charge and discharge rate capability of the battery. Safety problems (thermal runaway) often occur when dendritic lithium is deposited because the lithium cannot intercalate into the anode and/or cathode fast enough. The use of nanomaterials should therefore also improve battery safety. The use of nanomaterials will also reduce volumetric changes and lattice stresses, which improves the mechanical stability of the electrodes.

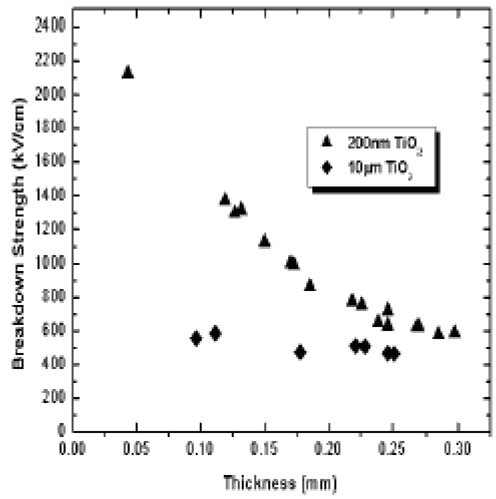

Figure 15 - Comparison of Breakdown Strength of Nano- and Micro-Structured TiO_2 [42]

Supercapacitors: The impact of nanotechnology on supercapacitor development will be similar to that described above for batteries. Increased surface area is increasing the maximum power density available.

Fuel Cells: The present design used for fuel cells is, in most cases, two-dimensional. In recent years, it has been realized that the potential of both battery and fuel cell systems can be substantially improved through the use of 3-D architectures, which optimize power and energy density while maintaining short ionic transport distances. Work in this area is being carried out under a US MURI project on "Three Dimensional Architectures for Electrochemical Power Storage" and has been the subject of a recent review [46].

Performance Projections for Pulsed Power Components:

Improved intermediate and high power storage is critical for the development of compact pulse power systems. A summary of the performance characteristics of various possible storage elements is given in Table 12.

Table 12 - Attributes of Potential Pulsed Power Storage Elements

Storage Element	Maximum Energy Density (Wh/kg)	Maximum Power Density (kW/kg)
Electrostatic Capacitor	0.01 - 0.05	10,000
Electrolytic Capacitor	0.05 - 0.1	1,000
Supercapacitor	1 - 5	10 - 100
Flywheel	5	0.4
Lithium-Ion Battery	225	1.5 - 2.5

The general power requirements for some selected applications are given in Table 13. From this Table, it is seen that the energy requirements for some of the applications, such as an electromagnet (EM) gun are exceedingly demanding with about 40 MJ being required. It is clear from these numbers that there needs to be a tradeoff between the stored energy and power densities to minimize the size of the storage element. Source operating voltage also needs to be taken into consideration. In some application, such as the generation of HPM, high voltages (~ 1MV) are required to drive the microwave generator.

Table 13 - Power Requirements for Some Selected Pulse Power Applications [10]

Device	Energy/Pulse (kJ)	Peak Power (GW)	Peak Voltage (kV)	Pulse Duration (μs)
EM Vehicle Stopper	0.1	0.002 -0.01	600	~ 0.01
HPM	40	4	1000	0.05 - 1
ETC Igniter	400	0.4	10	1000
ETC Gun	4000	1	16	4000
EM Gun	40,000	7	10	6000

5.5 Energy Harvesting

Present Status.

Energy harvesting refers to the generation of (electrical) energy from the environment by direct energy conversion. Energy harvesting devices can generally be divided into two groups - those powered by human activity and those powered from other (non-human) environmental sources. Three types of energy can potentially be tapped into. These are kinetic, electromagnetic radiation (including solar and RF sources) and thermal energy. For human energy devices, only kinetic and thermal energy is available. A number of commercial devices are available that use human kinetic energy for battery charging. These include a variety of devices that are hand cranked (radios, flashlights and cell phone battery chargers) or shaken (watches). More recently, the use of heel strike, piezoelectric devices have been proposed [47] to harvest soldier energy during walking. It is important to realize that the amount of energy that can be harvested in this manner is quite limited. For example [11], a 2 W heel strike system would only generate 16 Wh during an 8 hour walk. This is only 10% of the capacity of a BA-5590 battery. The effect of this type of energy harvesting on soldier fatigue needs to be investigated. While energy harvesting may be useful as a source of back-up or supplemental power, it seems unlikely that it will be used as a prime source of power for the Soldier System requiring ~20 W. For systems requiring more modest powers, it is a possibility that could be considered.

Energy can also potentially be harvested using the thermal energy from the body. Small thermoelectric generators have been developed [47] that convert body heat into electrical energy. It is claimed that 40 μW at 3 V can be generated from a 5°C gradient in temperature. This source could be useful for powering certain sensors such as physiological sensors for example.

Environmental energy sources include kinetic energy from the movement of wind or water as well as vibrational energy, electromagnetic energy from solar radiation or transmitted sources and thermal energy from vehicle engines or stoves. Harvesting of these sources of energy is of particular interest for powering wireless sensor networks because the source of energy is unlimited. In most cases, however, these sources of power are intermittent which requires energy storage (battery or capacitor) as well as power conditioning to stabilize the output.

Kinetic energy (from wind, water or structural vibration) can be harvested by converting this energy into either the displacement or mechanical deformation of some structure inside the energy harvesting device. The deformation or displacement is then converted [47] into electrical energy through the use of a piezoelectric generator, an electrostatic generator, or a magnetic induction generator. In general, it can be said that the energy that can be harvested with a small device is quite limited and likely to be mainly useful for powering low power, microelectronic devices such as sensors. Large scale generation, for example with large wind generators, is of course possible; however, these require large fixed installations are not useful for the mobile soldier.

Solar energy has considerable potential for providing power to soldiers in the field. In bright sunlight, the solar intensity is approximately 1 kW/m^2 on an optimally oriented surface. Until recently, the available photovoltaic technology was silicon based and consisted of rigid and fragile crystalline silicon cells which had a high energy conversion efficiency (15-23%) but were also expensive. While suitable for fixed installations, such as the High Arctic Data Communications System [48], these photovoltaic panels could not easily be configured for the mobile use. The development of inexpensive, flexible (plastic) solar cells by companies such as Konarka [49], Iowa Thin Films [50], and Nanosolar [51] is changing this. The US Army is now field testing portable chargers, tents and sensor systems that contain these new photovoltaic materials that can be rolled up or folded for easy storage and can even be integrated into the fabric of tents, the skins of vehicles and, eventually, into clothing. Because of the intermittent nature of solar energy, solar energy systems will need to be integrated with some method of energy storage. This energy can be used for battery recharge or even the generation of hydrogen for use in fuel cells.

RF energy densities from communication transmitters are typically very low. In urban environments, where there are many fixed and mobile RF sources, it might be possible to harvest enough energy to operate low power sensors.

The harvesting of thermal energy using thermoelectrics is also a possibility. Thermoelectric devices have a number of attractive features such as long life, the lack of moving parts, low maintenance and high reliability. In spite of these advantages, their use to date in both civilian and military applications has been very limited primarily due to the low efficiency of these devices. The main difficulty has been that available thermoelectric materials have limited performance. Thermoelectric materials are often characterized in terms of the dimensionless "figure-of-merit", ZT, which is directly related to the efficiency of the thermoelectric generator. Recent advances using nanotechnology are offering the promise to greatly increase thermoelectric efficiency. Because of this, there is new interest in the commercial field with automakers such as General Motors and BMW looking at thermoelectrics as a replacement for alternators thereby improving fuel efficiency. In this scenario, the thermoelectric generator could be wrapped around a car's exhaust pipe, to harvest the waste heat and produce electricity. Similar applications could be found in the military. Harvesting of thermal energy from vehicles and stoves could reduce fuel usage in the field. A US company, BSST a subsidiary of Amerigon, already has a large production of thermoelectric car seat heaters and coolers and is active in the materials development area.

The properties of thermoelectric materials are conflicting. They need to conduct electricity well but at the same time conduct heat poorly or else the thermoelectric will heat up and the efficiency will fall. The challenge is that when electrical conductivity goes up, heat conductivity tends to go up as well. Nanotechnology is offering a potential solution to this problem. For example, researchers [52] have created materials with molecular lattices that interrupt vibrations from heat, keeping the heat from thermally conducting, while allowing electrons to move freely.

Future Directions/Impact of Nanotechnology:

Photovoltaic Materials:

The development of inexpensive, flexible (plastic) solar cells by companies such as Konarka [49], Iowa Thin Films [50], and Nanosolar [51] is offering new possibilities for the use of solar energy in the field. These new photovoltaic materials can be rolled up or folded for easy storage and can even be integrated into the fabric of tents, the skins of vehicles and, eventually, into clothing.

Themoelectric Materials:

The central issue in thermoelectrics research is to increase thermoelectric figure of merit, ZT, to increase conversion efficiency. The best thermoelectric materials have low thermal conductivity as in a glass and a high electrical conductivity as in metals and are found in heavily doped semiconductors. Insulators have poor electrical conductivity and metals have good thermal conductivity. In semiconductors, the thermal conductivity has contributions from both electrons and phonons with the largest contribution usually coming from phonons. It has recently been found [52], that low-dimensional materials, such as quantum wells, superlattices, quantum wires, and quantum dots offer new ways to manipulate the electron and phonon properties of a given material. In the regime where quantum effects are dominant, the energy spectra of electrons and phonons can be controlled through altering the size of the structures, leading to new ways to increase ZT. Development of nanomaterials having improved ZT is an active area of research [52].

5.6 Small Nuclear Reactors

Present Status:

Compared to fossil and solar energy, nuclear power is characterized by an extremely high mass and volumetric energy density. As an example, the fissioning of 1 gram of U-235 has equivalent energy to the burning of 1.3×10^6 grams of Diesel fuel. In addition, unlike combustion, there is essentially no emission from the fission process. There should be no operational limitations in terms of temperature, location, etc., once sited. The fuel replenishment interval could be several years to the life of the reactor. Power sizes can be from 100's of kW(e) (1000's kW(t)) to 100's of MW(e) (1000's MW(t)), depending on modularity in some designs and the conversion method to electricity. The fissile fuel will be efficiently utilized, but the conversion step to electricity could have efficiencies as low as 10 %. Fuel storage should not be an issue as the whole core would be exchanged as a unit or disposed of with the reactor at the end of life. Transportation of new and exposed fuel should not be an issue as licensed shipping containers are available.

A number of small fixed and mobile nuclear reactors have been built largely for military purposes. By far the largest numbers of these are the reactors that are used in nuclear powered submarines by many nations. The use of a nuclear reactor in this application provided essentially unlimited submerged endurance. In the US, seven small land-based and one ship-mounted reactors were built for the US Army between 1954 and 1976. Several of these were designed for remote use and produced both heat and electricity. The reactors were designed to be transportable and to be suitable for rapid installation in remote areas. The total installed capacity of these reactors was 95 MW thermal and 18 MW electrical. The units ranged in size from 300 kW electrical to 18 MW electrical. All of these reactors were decommissioned in 1976. For remote or secure power supply, a small reactor that could supply both space heating and electricity would be very competitive to other technologies, which, at this time, are using fossil fuels. In terms of capacity factor, intervals between refueling, overall operational cost, security, etc., it should be superior to other technologies. In terms of initial capital cost, licensing time and training (for even an essentially self–running system), it would likely be inferior. The likely military applications would be the more critical ones such as remote locations (e.g. Alert, deep-sea Arctic port, northern airfield, etc), and operational bases and stations with need for back-up power (e.g. flight lines, dockyard support, berths for visiting nuclear submarines, etc).

The possibility of using nuclear power to generate alternate fuels has been considered by the US Army as a means of reducing logistics requirements for conventional fuels. A recent review [53] by Pfeffer and Macon discusses the feasibility compact nuclear reactors for generating hydrogen (as a replacement for fossil fuels) and potable water. This study was a follow up to earlier US Army studies that examined the feasibility of developing a nuclear-powered energy depot. This energy depot was aimed at solving the logistics problem of supplying fuel to military vehicles on the battlefield. It was proposed that the nuclear power plant would be combined with a fuel production system to turn readily available elements such as hydrogen or nitrogen into fuel, which then could be used as a substitute for gasoline or diesel fuel.

Future Directions:

There appears to be interest worldwide on small nuclear reactors with a good likelihood that a system will be installed somewhere within a 20-year time frame. The incentive for this development is based on future fossil fuel availability, environmental effects and pricing as well as maturing of experience, designs and components in the nuclear industry. The economies of scale will be in multiple units rather than size of a single unit. The appeal to anti-nuclear critics will be the avoidance of centralized, big utility run systems with their perceived cost overruns and complexity. It is conceivable that, within this time frame, a safe, local and more understandable energy source will become accepted, just as the SLOWPOKE-2 research reactor has in university environments.

A synopsis of several systems under consideration follows:

A U.S. Department of Energy (DOE) collaboration between three national laboratories has resulted in a small, sealed, transportable, autonomous reactor (SSTAR) concept for electricity (10 to 100 MWe), heat, freshwater and hydrogen production. The reactor is designed to be shipped to the site, weighs <500 tons and will be 15 m high by 3 m wide, and will produce energy for up to 30 years without refuelling. Further collaboration with the Central Research Institute for Electric Power Industry (CRIEPI) in Japan started a review of a modified design in 2003. CRIEPI and Toshiba have developed a Toshiba 4S (Super Safe, Small and Simple) concept that will provide about 10 MWe for 30 years. Toshiba is apparently offering a free reactor, to be installed before 2010, to the 700-person town of Galena, Alaska, who will only pay for operating costs so that the present diesel generated electricity cost will go from 28 to <10 cents/kwh. The City council has approved this offer in Dec 2005, but the Nuclear Regulatory Commission has to approve the installation.

Compact reactor concepts based on high-temperature, gas-cooled reactors are attracting attention worldwide. A South African firm, Pebble Bed Modular Reactor (PBMR) Pty, is apparently constructing a demonstration plant near Cape Town by 2010. Each reactor module generates about 170 MWe. The company is trying to license its technology in the U.S. and has signed a MOU with Chinergy, a Chinese company planning to build a demonstration plant near Beijing, where there is an experimental research model at Tsinghua University. A similar design is the remote site-modular helium reactor (RS-MHR) being developed by General Atomics.

Several other concepts exist such as the Long-Life Safe Simple Small Portable Proliferation-Resistant Reactor (LSPR), 53 MWe, from Tokyo Institute of Technology, Japan; the Encapsulated Nuclear Heat-Source (ENHS), 50 MWe, from UC Berkeley, U.S.; and NEREUS, 8 MWe, reactor from the Netherlands, similar to the PBMR.

Several Canadian proposals are possibly more feasible, from a Canadian licensing point of view. One is AECL's Nuclear Battery, 600 kWe, developed in the 1980's, which could be reconsidered. The report, AECL –9570, dated 1988, is a summary of the design. The second is the SLOWPOKE Energy System (SES), 10 MWt, for which a prototype, the SLOWPOKE Development Reactor (SDR), 2 MWt, was actually built at Whiteshell. Lastly, Dr. Hilborn, one of the developers of the SLOWPOKE-2, is promoting a homogeneous version for molybdenum-99 production. Possibly, a cogeneration capability would be feasible.

Further investigation of the design, technological details and requirements, costs, etc., would be required to obtain more definitive information on all or some of these concepts.

Nuclear power is expected to grow in the 21st century, with potential benefits applicable to the military. The development of small, modular nuclear power reactors in mobile or portable configurations is likely for power and heat production at remote locations and for the production of fuels and potable water for combat forces deployed in remote areas and reduced logistical requirements. Licensing by the regulatory bodies is likely to be time-consuming. The next important step would be the progression from completing the conceptual design to laboratory tests of components or electrically heated cores to a possible fully working prototype and, possibly, a demonstration installation at an appropriate site.

5.7 Radioisotopic Power Sources

Present Status:

Radioisotopes can provide a very long-lived heat source that can be used to power a thermoelectric, thermionic or engine generator. In such a heat source, the heat is produced by the natural radioactive decay of the isotope. The main isotopes that have been used for this application include:

Co^{60},	5.25 y half life,	0.31 MeV beta, 1.37 MeV gamma
Sr^{90},	25 y half life,	0.54 MeV beta
Pu^{238},	92 y half life,	5.14 MeV alpha, 0.04 MeV gamma

Radioisotopic thermoelectric generators (RTGs) have been used in a limited number of applications in the past 3-4 decades, with perhaps the most common being spacecraft, remote Soviet lighthouses, and pacemakers. The table below captures some relevant information for five selected RTGs. The first three are for space applications, the first being the RTG used during the Apollo program, the second being the RTG on the Cassini probe (the largest RTG to-date, launched 1997), and the third being a planned RTG for future Mars rovers (launch ~ 2009). One can see that in 30 years, no notable progress has been made with respect to efficiency (conversion of thermal power into electrical power), with concomitant stagnation with respect to power density or energy density. The Soviet lighthouse RTG differs from the spacecraft RTGs mainly in that it used strontium-90 (a beta emitter) as opposed to plutonium-238 (an alpha emitter) and this mandated the use of large amounts of radiation shielding, producing a tremendous decrease in power and energy densities. The plutonium pacemaker RTG is obviously built on a much smaller scale, and this produced significantly decreased power density and energy density.

RTGs have been and are currently characterized as extremely reliable and relatively simple power sources, with no moving parts and employing technology no more complicated than a thermocouple. As a result, there are few operational (environmental) limitations on the use of RTGs. Furthermore, the energy density of an RTG is truly impressive, assuming that a long-lived isotope like Pu-238 is used. On the other hand, the inefficiency of the thermocouple to convert thermal energy into electrical energy results in a low power density (approx. 25 W/kg for a mid-sized generator), meaning that these generators are used only in niche applications where there is a long-term need for continuous power in completely unattended mode.

Table 14 - Characteristics of Radioisotopic Power Sources

Name	Electrical Power (W)	Efficiency	Total Mass (kg)	Power Density (W/kg)	Energy Density (Wh/kg)
SNAP-27	73	4.9%	20	3.6	4×10^6
GPHS-RTG	300	6.8%	55.5 [0.158 m^3]	5.4 [1900 W/m^3]	6×10^6 [2.1×10^9 Wh/m^3]
MMRTG	110	5.5%	30	3.7	4.1×10^6
Soviet Lighthouse	10	4.3%	560	0.02	22000
Plutonium Pacemaker	300×10^{-6}	0.4%	?? [12×10^{-6} m^3]	?? [25 W/m^3]	?? [28×10^6 Wh/m^3]

The other major impediment to the use of RTGs is the tremendous quantity of radioactive material employed. The GPHS-RTG, for example, employed 130 kiloCuries (kCi) of Pu-238 to produce 300 W. This quantity of radioactive material, while only 23 kg, would constitute an extremely grave hazard if it fell into the wrong hands. Even the pacemaker battery used 2.5 Ci, which could be used to produce considerable disruption if optimized for use in a dispersal device.

It is worth noting that another major impediment to RTG use is cost. NASA estimates from year 2000 of the cost to be paid to the Department of Energy to assemble, service, and support a space-bound RTG (200-300 W) were in the \$40M-\$50M dollar range. Again, these costs are prohibitive except in the most specialized of applications.

Future Developments:

Research & development of RTGs is in the area of the conversion of thermal power to electrical power, which until now has always been done by thermocouples. Thermocouples have conversion efficiencies of less than 10%, and this is reflected in the table above. Some research is working toward the improvement of thermocouple systems for milli-watt and multi-watt RTGs, promising to deliver 8% efficiency on these scales. Other technologies have been discussed or researched; these include thermionics, alkali metal thermoelectric converters (AMTECs), thermophotovoltaics (TPVs), Rankine engines, Brayton engines, Stirling engines, beta photovoltaics, thermally pumped lasers, nitinol (bimetallic) engines, pyroelectric energy conversion, and Nernst (thermomagnetic) generators. Brief statements on some of these follow:

- Thermionic systems have efficiencies in the 10-20% range and have been experimentally demonstrated. There is an incompatibility, however, between the normal operating temperature of a Pu-238 RTG and that of a thermionic converter. It is possible that R&D effort on either component could bridge this gap.

- AMTEC promises 20-40% efficiency, and may be available in the near term. Work published in 1992 with a GPHS source coupled to an AMTEC produced 55 W of electrical power, with a net efficiency of 25% and a power density of 18 W/kg.
- Development is continuing on TPV systems, with expected efficiency of 15-20% and power density up to 15 W/kg, potentially in the near term.
- Rankine engine development continues, but appears to be aimed at power conversion from nuclear reactors.
- Brayton engine systems are seeing some attention, promising a power density of 9-13 W/kg in the short term.
- Stirling Radioisotopic Generators are undergoing development, and an SRG is in the running to power a host of space probes from 2009 out. The efficiency of these systems is expected to be 30% or more, but this does not show up as a substantial increase in power density, which still sits at 8 W/kg. The efficiency is used to decrease the amount of radioactive material required, by a factor of 4.

As mentioned above, RTGs have only found use in niche applications where there is a need for extremely reliable, completely unattended, long-term continuous power. The use of RTGs in other applications is mitigated by its bulk (several times more weight per unit power than a gasoline generator, for example), its cost (tens of millions of dollars for large RTGs), and the implications of using a highly radioactive source. Technological change promises to reduce the weight per unit power or the amount of radioactive fuel per unit power by factors of three or more. While this makes the RTG more competitive in terms of weight, it is unlikely to make much of a difference when it comes to the radioactive fuel (which, even reduced by an order of magnitude, would still be extremely large). Changes to costs might scale with the amount of radioactive fuel (to some extent), but overall costs would still be astronomical. For these reasons, it is unlikely that this technology will be embraced by the military.

Impact of Nanotechnology:

Development of improved thermoelectrics, thermovoltaics, and other power conversion technologies will no doubt be dependent on advances in materials science and the application of discoveries at the nano-scale (quantum wells, for example). That being said, nanotechnology does not seem to have a great role to play in the development of RTGs.

5.8 Hybrid Systems and Power Management

Present Status:

The military has a need for power sources having high energy and power densities, the capability of operation over wide environmental conditions and the ability to use military fuels. In many cases, there is no single power source that can meet the requirements; however the overall performance of the power system can be improved by hybridization. As an example, consider a hybrid battery/fuel cell power system to meet the requirements of the dismounted soldier. In general, the energy density of batteries is low and the batteries by themselves lack the capacity to provide the long-term power that the Soldier System requires. Newly developed fuel cells (such as DMFCs) of reasonable size may provide the necessary energy, but are then unable to provide the high peak power occasionally demanded by these systems. Hybrid fuel cell/battery systems can combine the high energy density of fuel cells with the high power density of batteries. The hybrid system may also have a number of advantages over each standalone component. For example, the battery can assist with fuel cell start-up by providing the majority of the load power during fuel cell warm-up. The battery can also condition the power output from the fuel cell by acting as a buffer to provide a voltage range that is acceptable to the equipment. A hybrid system can allow both components to be of smaller dimensions and to operate with higher efficiency since neither would have to provide full load and capacity.

As a second example, consider the development of a fuel cell powered cell phone. While having high energy density, micro fuel cells suffer from low power density and a relatively wide operating voltage. These difficulties can be overcome by using a fuel cell/supercapacitor or fuel cell/battery hybrid. Power conversion electronics is also an important element of such a system. For example, a DC/DC power converter can be placed between the fuel cell and the battery to greatly augment the peak output power while reducing the system weight and volume. The use of a low voltage DC/DC converter with a wide voltage input range provides flexibility to the fuel cell design and can optimize fuel usage and increase reliability.
Hybrid power sources can be almost any combination of power generators and/or energy storage systems. These combinations are used to improve the performance of the overall system, to make up for weaknesses of one of the components or for basic requirements.

Future Directions:

Modelling: Because of the very large number of possible hybrid combinations and mission scenarios, modelling is going to be an important tool for the development of hybrid power sources. Models are required for individual components (batteries, fuel cells, electronic components etc) and for the analysis of a wide range of mission scenarios. Algorithms need to be developed to optimize energy usage. Many new hybrid power sources will likely be microprocessor controlled so energy optimization can be done in real time. The Power Sources Laboratory at the University of Southern Carolina is developing [54] a Hybrid Power Sources project in support of the requirements of the US Marines. Modelling is a substantial element of this program. Table 15 is an example that illustrates the impact that hybridization can have on system performance.

Table 15 - Impact of Hybridization on Power Characteristics [54]

System Parameter	Fuel Cell	Fuel Cell/Battery Hybrid
Weight (kg)	2.9	3.3
Volume (l)	5.1	5.1
Maximum Power (W)	35	140
Power Density (kW/l)	6.9	27.5

Power Source Management Electronics: As mentioned above, power conversion electronics is going to be an increasingly important element of hybrid power systems. In many cases there is going to be a mismatch between the voltage and current characteristics of the various elements of the hybrid system, which needs to be addressed by power conversion. For example, in a cell phone power system, a DC/DC power converter can be placed between the fuel cell and the battery to greatly augment the peak output power and reducing the system weight and volume. The power converter is used to boost the fuel cell voltage in order to operate the phone and charge the battery or supercapacitor. Custom designed compact, efficient and low cost power conversion electronics is going to be needed. The use of a low voltage DC/DC converter with a wide voltage input range provides flexibility to the fuel cell design and can optimize fuel usage and increase reliability. It is important to integrate the design of the power converter with the rest of the power system. Through early consideration of power conversion design, a small and inexpensive unit can usually be built.

Electronic management is also going to be an important element in optimizing power system output. As an example, it has recently been shown [55] that the application of short duration, high-current pulses to a PEM fuel cell can alleviate the effects of anode poisoning and significantly improve stack output. The US Army has recently issued [37] a call for proposals under the SBIR program for a "Compact Direct Methanol Fuel Cell Power System Using Pulsed Electrical Control" to investigate the utility of this approach. This approach can be used for PEMFCs using reformate [56], methanol [57] or formic acid [35] as fuels. Other potential uses of power management electronics includes battery equalization, overcharge protection and optimization of cell life.

Power Awareness and Power Management

Developments in military technology are revolutionizing the future CF battlefield and security environments. In many cases, provision of power is limiting operational capability. In this report, we have examined and assessed the capability of a variety of power sources to meet future CF requirements. If demanding requirements, such as those of the Soldier System, are going to be met, in addition to the development of high energy density power sources, it is equally important that power consumption be minimized through the development of power and energy efficient technologies including low power electronics, reversible 'adiabatic' processing, and power awareness and management. The challenge is going to be to maximize performance while at the same time minimizing power consumption.

While a detailed assessment of these energy-reducing technologies is beyond the scope of this study, it is worthwhile to identify this important area of technology and to briefly describe some of the important research activities in this area.

To date, power reduction in digital circuits has been mainly driven by increasing the transistor density on integrated circuits - according to the so-called "Moore's Law". Increasingly, however, as more transistors are integrated on a chip to enable more functions and higher frequencies to be used, the total power consumption rises and heat dissipation becomes a major issue.

To overcome this, new techniques are needed and are being developed. One such technique under development is reversible (or adiabatic) computing [58] which enables electrical energy to be reused from cycle to cycle rather that discarded, as is now presently the case. When information is discarded, as in traditional computing, it contributes to the heat load. Reversible computing will increase energy efficiency and allow heat-limited systems to run much faster.

System designers are also turning to the concepts of power (and energy) awareness and dynamic power management to reduce power consumption. In this concept [59], power consumption is sensed and then reduced by dynamically adjusting the system so that it only delivers the performance that is required at a given time. One of the oldest techniques that has been used is to shut down unused parts of the system when they are not being used. With digital circuits, a technique known as "dynamic voltage scaling" (DVS) has been developed [60] which is more effective than shutdown. Reducing processor voltage reduces the processor speed so that it can be matched to the task at hand. This results in substantial power savings with no penalty in performance.

While the energy consumption of digital circuits has rapidly decreased, due to device integration (Moore's Law) and the development of innovative techniques such as DVS, the same is not true for communication systems. The radiated power required for communication, which is dictated by transmit distance, can often dominate power consumption. While shutdown-based schemes can be used to reduce power, there is a need to develop dynamic scaling methods similar to the DVS scheme used for digital circuits. One such scheme that has been investigated [61] involves dynamic modulation scaling (DMS). This technique allows the radio to dynamically change its modulation. Originally, this technique was used to maximize the system throughput; however, the technique can also be used to maximize energy efficiency while maintaining the required throughput.

Impact of Nanotechnology:

The major impact of nanotechnology will be related to the development of individual power source elements (e.g. batteries, fuel cells and supercapacitors) and has been described in preceding sections of this report. Improvements in and custom design of power conversion and management electronics will continue to be an important element of the design of hybrid power sources.

6. ANALYSIS OF POWER SOURCE OPTIONS FOR VARIOUS APPLICATIONS

6.1 Introduction

In this section, an analysis of the ability of various power source options to meet the requirements of a number of important military applications is carried out. Factors identified include total system weight, state of development in terms of technology readiness levels (TRLs) and supply logistics.

6.2 Power for the Soldier System

Future Soldier Systems are expected to contain a wide variety of advanced technologies including digital communications, GPS navigation, integrated helmet display, protective clothing, suit cooling and improved weapons. The battery systems presently being used to power portable electronics will be unable to meet these future requirements.

To carry out our analysis the parameters listed in Table 16 have been used:

Table16 - Parameters Used to Evaluate Soldier System Power Requirements

Power Source Parameter	Value
Average Power (W)	20
Run Time (hours)	72
Total Energy Required (Wh)	1440
Peak Power (W)	100
Duty Cycle (% Peak to Average)	1
Peak Energy Required (Wh)	72
Total Weight (kg)	2.4
Energy Density (Wh/kg)	600
Power Density (W/kg)	42

In this analysis we have included selected primary and rechargeable batteries, direct methanol and chemical hydride fuel cells, fuel cell/battery hybrids and microengines. Table 17 summarizes the results of this analysis.

Table 17 - Comparison of Power Sources to Meet the Soldier System Requirement

System	System Mass (kg)	Specific Energy (Wh/kg)	TRL
Li-Ion Battery	6.4	225	9
Li/SO_2 Battery	5.76	250	9
DMFC	4.5	320	5
H-PEMFC	3.7	389	6
DMFC/Li-Ion Hybrid	2.64	545	5
H-PEMFC/Li-Ion Hybrid	2.64	545	6
MEMS Turbine (5%)	2.4	600	2
MEMS Turbine (10%)	1.2	1200	2

The following are some comments related to the data in this Table:

1. The Li/SO_2 and Li-Ion batteries are fully developed and are already in the CF inventory. The energy density of these batteries falls far short of the 600 Wh/kg target for future Soldier System power however.

2. Weights and energy densities for the DMFC and H-PEMFC were based on the data and estimates collected for 20 W systems (section 5.5). In order for the fuel cell to meet the peak power requirement of 100 W, it was assumed that the stack size had to be increased by a factor of 5. Using data reported by Mesoscopic Devices [64] for their 15 W DMFC, the stack weight was taken as 33% of the total system weight. For a 100 W system, this fraction was scaled to approximately 70%. Because of the relatively higher power density of hydrogen stacks, stack weight was assumed to be 25% of total system weight for a 20 W H-PEMFC. Scaling to 100 W was done in a similar fashion.

3. For the fuel cell/battery hybrid systems, it was assumed that the battery needed to have the full capacity to meet the 1% peak power requirement (about 45 minutes of run time). The size of the battery might be able to be reduced if, for example, it was determined that the peak requirement consisted of four bursts of approximately 11 minutes each with sufficient time to recharge in between. Reducing the battery size would increase the overall energy density of the system.

Based on the results presented the following general conclusions have been reached regarding selection of a 20 W Soldier System power supply having characteristics as outlined in Table 17.

1. To meet the Soldier System requirement, it will be necessary to use an energy conversion device such as a fuel cell or microengine. Battery energy densities are too low to meet the requirement.
2. To meet the peak power requirements, it is likely that hybrid fuel cell/battery system will be needed with the battery meeting the peak power requirements while the fuel cell meets the average power requirements. Both direct methanol fuel cells and chemical hydride fueled PEM fuel cells have the potential to meet the average power requirements and they are close to the same state of development (TRL 5-6). DMFCs have problems with low power density and crossover of methanol from the anode to cathode sides but it appears that these problems may be overcome with new stack design. Hydrogen PEM stack technology is well developed; however, fuel and product handling over a wide range of conditions is likely to be an issue with H-PEMFC development. Ultimately, it seems likely that fuel logistics and cost will influence the fuel cell technology that is chosen.
3. Micro engine generators have the potential to provide a very high energy density power source to meet the Soldier System requirements. This technology is at a very low state of development and development costs will be high.

6.3 Tactical Field Power

There is a strong requirement for tactical field power. Power is required for recharging batteries, O&M on equipment, field medicine, messing and water. At the present time, this need is met using diesel or gasoline engine generators. The requirement for tactical power with reduced acoustic, thermal and electromagnetic signature has existed for many years. Cogeneration of heat to reduce overall fuel consumption is also desirable. PEM fuel cells are potentially attractive because of their low operating temperature and low acoustic noise which would allow siting of the generator so that waste heat could be used for water and/or space heating. This type of system is under intensive development in

Japan for residential use. Ebara Ballard have reported development of a system with as high as 92% combined (electrical +thermal) efficiency for their 1 kW combined heat and power fuel cell generator. The electrical efficiency was 34%. Solid oxide fuel cells (SOFCs) are also under development for residential applications. These systems have the advantage that they offer higher quality waste heat and can handle logistical fuels such as JP-8 more easily because of the higher operating temperature. They are at a lower state-of-development than the PEM systems. Stack durability especially for intermittent use is an issue. Table 18 gives estimated characteristics for several field generators. The general requirements examined in this analysis include:

1.5 kW power level
Silent operation
Liquid (tactical) fuel operation
Lightweight
Reduced thermal signature
Long life/low maintenance

Table 18 - Projected Characteristics for 1.5 kW Field Generators

Parameter	**Mechron 1.5 kW Diesel** (1)	**Honda 1.6 kW Gasoline** (2)	**Ballard Nexa PEM** (3)	**Acumentrics SOFC** (4)
Electrical Efficiency (%)	16	16	26	26
Thermal Efficiency (%)	0	0	46	46
Fuel	Diesel	Gasoline	Diesel	Diesel
Fuel Consumption (l)	1	1	0.6	0.6
Weight (kg)	50	21	30	150
Noise Level	77 dBA @ 7m	59 dBA @ 7m	55 dBA @ 1m	55 dBA @ 1m
TRL	9	9	8	6

Notes:
1. Scaled from data sheet for the Mechron 2 kW Portable Military Field Generator
2. Honda EU20i Camping Generator data Sheet
3. Based on Nexa Power Module (stack) data. Balance-of-Plant assumed equal mass as stack. Electrical and thermal efficiencies as given by Ebara Ballard. Estimate of acoustic emission taken from data for IdaTech FCS-1200 PEM fuel cell
4. Based on scaled mass from Acumetrics RP-SOFC-5000. Electrical efficiencies reduced to account for Diesel reformation losses. Acoustic emission assumed the same as PEMFC.

Fuels cells offer lower acoustic and thermal signatures compared to conventional engine generators. The possibility of cogeneration of electricity and heat, which is possible because of lower noise levels, gives very high overall efficiency, which could substantially reduce fuel consumption. PEM fuel cells are at a higher state of development having been extensively tested under the US DoD Residential Fuel Cell program [31].

6.4 Wireless Sensor Networks

To meet the requirement for sensor elements to be very long lived and compact, they need to operate at extremely low power. To achieve this, it is necessary to use very low power hardware and low duty cycle operation techniques (ie the sensors spend a lot of their time in "sleep" mode). In this section we examine options for powering sensors with the following characteristics

Average Power	-	500 µW
Life	-	5 years
Cost	-	low

One of the highest energy density primary batteries available is the $Li/SOCl_2$ battery. A single AA-cell has a capacity of 2450 mAh, an operating voltage of 3.6 V, weighs 16 g and has a volume of 8.65 cm^3. Three cells would be required to meet a 5-year requirement.

As an alternative power system, consider using a photovoltaic system to harvest available solar energy. As an example, in Toronto the mean daily global solar radiation that is received on a horizontal surface during December (the worst month) is 3.917 MJ/m^2. Assuming a 12% efficiency, a 1 cm^2 PV collector could generate 540 μW - enough to power the sensor. Summer insolation levels are about 7 times higher. To allow for extended periods of very bad weather, we assume that 2 week storage is needed which amounts to about 50 mAh. A Varta PLF 263441C Lithium-ion battery contains substantially more than this (320 mAh) and has a volume of 3.6 cm^3 and weighs 8 g. To allow for the possibility that snow cover could block solar collection for a portion of the year, inclusion of some primary battery storage capacity could also be considered.

A comparison of three power source options for meeting the sensor requirement is given in Table 19.

Table 19 - Options for Powering a Wireless Sensor Network

Power Source	Mass (g)	Volume (cm^3)
$Li/SOCl_2$ Battery (3 cells)	48	26
Solar/Li-Ion Battery Hybrid	9	4
Solar/Li-Ion/$SOCl_2$ Battery Hybrid	25	13

The possibility also exists of using a "Nuclear Battery" to provide very long-lived, reliable power. In the 1970s a number of Plutonium 238 based batteries were developed to power cardiac pacemakers. Ultimately these batteries were superseded by the development of high energy density lithium batteries. Although a nuclear battery is a technically feasible option for powering sensors, the cost is expected to be prohibitive. The small nuclear battery developed by Numec Corp that produced 320 μW cost $3200 in 1974.

The above analysis shows that solar energy harvesting has the potential to substantially reduce the size and cost of the sensor power source.

6.5 Battery Recharge Using Solar Energy Harvesting

There is a growing need for portable power to recharge batteries for the Soldier System. The development of lightweight, flexible PV materials that can be integrated into tent fabrics provides the opportunity to provide a silent source of power.

As an illustration of the potential, the yearly average daily insolation on a horizontal surface in Toronto is 12.7 MJ/m^2. A PV array having 12% conversion efficiency would generate 17.6 W/m^2 under these conditions. Integration of such thin film PV materials into tents has been demonstrated by Iowa Thin Films (Figure 16). A total tent area of 20 m^2 would generate approximately 350 Watts - enough to recharge about 15 20W Soldier System batteries.

Figure 16 - Iowa Thin Films Solar Tent [50]

6.6 Central Power for a Remote Base

Central/fixed power represents the power needed in CF bases and wings as well as needed in deployable camps. Even though local hydro companies usually provide power at the bases and wings, backup power must also be considered. Typical power requirements are in the range from 100's of kilowatts to many megawatts.

In the future, as fuel supply diminishes and costs rise, nuclear power may become an attractive option as a secure source of energy for fixed installations. The use of nuclear power for the generation of alternative fuels such as hydrogen for use in fuel cells is also a possibility.

7. TECHNOLOGY READINESS LEVEL ASSESSMENT

The following is an assessment of the present state of development as well as a projected timeline for future development of selected power source technologies that have been selected because of their perceived importance to the CF/DND.

Table 20 - Technology Readiness Levels

Power Technology	2005	2010	2015	2020	2025	2030
20 W Soldier System Fuel Cell						
Soldier System Rechargeable Battery						
Cogen Fuel Cell for Mobile Applications						
Microengine for Soldier System						
Pulse Power for Burst Communications						
Pulse Power for EM Munition						
Energy Harvesting for Wireless Network						
Energy Harvesting for Battery Charging						
Small Nuclear for Remote Base						

Table 21 - Technology Readiness Levels Key

Level	Colour	Description
1		Basic principles observed and reported
2		Technology concept and/or application formulated
3		Analytical and experimental critical function and/or characteristic
4		Component and/or breadboard validation in laboratory environment
5		Component and/or breadboard validation in relevant environment
6		System/subsystem model or prototype demonstration in a relevant environment
7		System prototype demonstration in a operational environment
8		Actual system completed and 'flight qualified' through test and demonstration
9		Actual system 'flight proven' through successful mission operations

Description/Definitions:

20 W Soldier System Fuel Cell: A 20 W high energy density (>600 Wh/kg) fuel cell capable of providing the average power needed for the future Soldier System. Must be able to operate over a wide range of environmental conditions.

Soldier System Rechargeable Battery: A high power (> 40 W/kg), high energy density (>250 Wh/kg) rechargeable battery capable of meeting the peak power requirements for the Soldier System. This battery will probably be used as a hybrid combination with another power source. Must be able to operate over a wide range of environmental conditions.

Cogen Fuel Cell for Mobile Applications: A 1.5 kW combined heat and power fuel cell with low thermal and acoustic signature capable of providing power and heat in the field for messing, battery recharging, tent heating, communications etc. The low acoustic signature will enable siting so that waste heat can be recovered and utilized. This fuel cell should utilize military fuels.

Microengine for Soldier System: A 20W micro engine/generator capable of meeting the Soldier System requirements. This engine should utilize military fuels.

Pulse Power for Burst Communications: A compact pulse power system capable of meeting the requirements of a burst communication system.

Pulse Power for EM Munition: A very high power (~ 1GW), compact power source capable of driving an electromagnetic source that can be incorporated in a munition (such as an artillery shell). This system is likely to use an explosive material as its prime energy source.

Energy Harvesting for Wireless Network: A high energy density, very low power (~500 μW), long-lived and inexpensive power source drawing its prime power from the environment that is capable of meeting the power requirements of future wireless sensor networks.

Energy Harvesting for Battery Charging: A power source drawing its prime power from the environment that is used for battery charging in the field. This source is used to reduce the consumption of fuel as well as reduce acoustic and thermal signature.

Small Nuclear for Remote Base: A small nuclear power system capable of meeting the requirements of a remote base (e.g. in the Arctic). This system is used to reduce dependency on the supply of fossil fuels thereby increasing security of supply.

8. RECOMMENDATIONS:

Based on the information collected during the following specific recommendations for each of the power source areas:

Batteries: Military requirements for advanced batteries (e.g. lithium-ion) will be met, in most cases, through commercial development. Specific areas such as improvement of low temperature performance and/or power density may require attention. The use of nanomaterials as the active electrode materials appears to be a promising route for improving the rate capability and low temperature performance of rechargeable lithium batteries.

Small Fuel Cells: Direct methanol and/or chemical hydride PEM fuel cells appear to have the best chance of meeting the high energy density requirement of the Soldier System as well as other applications including robotic systems and some UAVs. There are limitations with both technologies that need to be addressed.

1. DMFCs suffer from low power density, water management problems and crossover of fuel from the anode to the cathode. The development of new 3-dimensional architectures and use of nanomaterials appear to be promising routes for investigation. The use of alternative liquid fuels, such as formic acid, is also a possibility that should be explored.
2. Chemical hydride fueled PEM fuel cells are based on well-developed PEM stack technology. The main problems that need to be addressed are associated with the fuel supply system. Compact, high energy density fuel supply systems are needed that can operate over a wide range of environmental conditions. The recovery and disposal or recycling of chemical byproducts in the field is an issue that needs to be addressed. The logistics of fuel supply, product disposal and cost may limit the military applications of these systems.

Large Fuel Cells: The need for "silent field power" has long been recognized. Both PEMFCs and SOFCs have the potential to meet this requirement. Commercial development is largely driving the development of both of these technologies. Japan, for example, has an extensive program aimed at the development of ~ 1kW PEM fuel cells for cogeneration of heat and electricity for residential use. In most cases these commercial systems are expected to use natural gas or propane as fuel. To adapt the commercial systems for military applications, an area that will require development is the development of compact reformers capable of using a logistic fuel such as JP-8. This is true for both PEMFCs and SOFCs. To meet military requirements, ruggedization of SOFCs will be required as well as development of the ability for rapid start-up and shut-down and frequent thermal cycling.

Microengines: Microengines are attractive for demanding applications such as the Soldier System because they offer the possibility of being able to use military fuels. This technology is, however, at a low state of development. While certain components of the microturbine have been successfully developed and tested, to date self-sustained operation (i.e., net power production) has not been demonstrated.

Pulse Power: A wide range of emerging military applications requires very high pulses of power for short duration. Some of these applications include: high power microwave and ultra wide-band weapons, electromagnetic guns, electric armour for military vehicles, non-lethal weapons, burst communications and RF munitions. This military technology is, in general, highly classified. In order to properly assess the threat and opportunities that these technologies present to the CF, conduct of research in this area will be important.

Energy Harvesting: The development of low cost, flexible photovoltaic materials will open up the possibility of harvesting solar energy for a wide range of military applications. These materials are being incorporated in to fabric materials and eventually could be used in tents, clothing and applied to the skins of vehicles. Solar harvesting has the potential to reduce fuel usage as well as thermal and acoustic signatures. Solar harvesting may also be applicable for small power sensor applications when combined with battery storage.

The development of high ZT (high efficiency) thermoelectric materials will offer the possibility for harvesting thermal energy in a variety of military applications. Nanotechnology is expected to play an important role in these developments.

Small Nuclear Power: In the long term, small nuclear systems may be developed to reduce the military's dependence on fossil fuels. Extensive development and regulatory approval is needed to field transportable power systems.

Radioisotopic Sources: Although radioisotopic sources have the potential to provide very long-lived and reliable sources of power, high cost and issues related to security and contamination are likely to limit their use to very specific applications such as in space.

Hybrid System and Power Management: Hybridization of power sources provides a means for combing the best properties of the various elements while avoiding the weaknesses. In order to meet many of the demanding requirements, such as the Soldier System requirement, hybridization is going to be necessary. To optimize this process, the development of modelling tools is going to be needed. Models of individual components, power electronics and hybrid systems are going to be needed. The development of specialized electronic components, e.g., for DC-DC conversion and voltage regulation, is going to be required. Power source management is an increasingly important area. For example, systems are needed to measure retained capacity, to equalize battery capacity in a string, optimize battery life and improve power output.

In addition to the development of high energy density power sources, the development of equipment with reduced power consumption will become increasingly important to the CF. Power awareness and power management are increasingly important areas that need to be addressed. A detailed assessment of these energy-reducing technologies is, however, beyond the scope of this report.

Nanotechnology: The use of nanotechnology is expected to have a major impact on the development of advanced power sources to meet the requirements of future military applications. The importance of this area of technology for future development is emphasized.

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Although DRDC published an exhaustive technical report (in August 2001) on technology trends in advanced power sources projected out to the year 2020, the terrorist attacks on the US on September 11, 2001 (and the consequent, augmented and more broadly-based defence and national security posture adopted by the CF/DND), together with rapid developments in power source technologies over the past five years, internationally, prompted DRDC to update the 2001 report, on a selected number of power source technologies or applications and to provide further guidance to DRDC's Advanced Power Source R&D program. Eight wide-ranging, power source technologies or applications were investigated, using the technique of "expert elicitation" (that is, using independent experts in the various and diverse technological fields), based on a standardized questionnaire, augmented by the contractor's own expertise (and his overall analysis of the experts' responses) in these diverse areas. In addition, each expert was asked about his/her view on the likely role of nanotechnology in each technological area or application. Following collection and analysis of all the data, the contractor made recommendations on the ability of each power source to meet the future requirements of the CF/DND, taking into account the Technology Readiness Level, for each technology or application.

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